2

NAVAL POSTGRADUATE SCHOOL

Monterey, California

AD-A241 240

DTIC
ELECTE
OCT 0 4 1991
S B D

THESIS

ANALYSIS OF OPTIMUM DEPOT LEVEL COMPONENT REPLACEMENT POLICY FOR RETROGRADED M1 ABRAMS TANKS

by

John A. Wilhelm

September, 1990

Thesis Advisor: Lyn R. Whitaker

Approved for public release; distribution is unlimited.

91-12038

REPORT DOCUMENTATION PAGE

1a Report Security Classification Unclassified	1b Restrictive Markings
2a Security Classification Authority	3 Distribution Availability of Report Approved for public release; distribution is unlimited.
2b Declassification Downgrading Schedule	
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)
6a Name of Performing Organization Naval Postgraduate School — 6b Office Symbol (if applicable) 30	7a Name of Monitoring Organization Naval Postgraduate School
6c Address (city, state, and ZIP code) Monterey, CA 93943-5000	7b Address (city, state, and ZIP code) Monterey, CA 93943-5000
8a Name of Funding Sponsoring Organization — 8b Office Symbol (if applicable)	9 Procurement Instrument Identification Number
8c Address (city, state, and ZIP code)	10 Source of Funding Numbers Program Element No · Project No · Task No · Work Unit Accession No

11 Title (include security classification) ANALYSIS OF OPTIMUM DEPOT LEVEL COMPONENT REPLACEMENT POLICY FOR RETROGRADED M1 ABRAMS TANKS

12 Personal Author(s) John A. Wilhelm

13a Type of Report	13b Time Covered	14 Date of Report (year, month, day)	15 Page Count
Master's Thesis	From To	September 1990	129

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes			18 Subject Terms (continue on reverse if necessary and identify by block number)
Field	Group	Subgroup	AGE REPLACEMENT POLICY, OPTIMAL REPLACEMENT, PREVENTIVE MAINTENANCE

19 Abstract (continue on reverse if necessary and identify by block number)

This study examines 48 M1 tank components for possible application of an optimum age replacement policy. The purpose is to support a broader study associated with the Reliability Centered - Inspect and Repair Only as Necessary (RC-IRON) program. The program provides depot level maintenance to tanks transferred or retrograded from Germany to the United States. An optimal age replacement policy reduces the number of failures while minimizing the cost associated with failure by replacing some older components before they fail. The component data for this analysis was drawn from the Field Exercise Data Collection (FEDC) at the National Training Center (NTC), Fort Irwin, California.

This thesis begins with a discussion of a methodology for determining an optimal replacement time. Distribution analysis is performed on component lifetimes as well as delay and repair times due to failure. The various costs associated with failure are estimated. The application of an age replacement policy was found to be beneficial for a few components and only when they had a high down-time cost. A graphical procedure is used to show sensitivity of the optimum policy to changes in cost. Component simulations are performed to pretest the results of a proposed maintenance policy. A six component system is simulated to demonstrate how the components could be tied together for later system level analysis. Although this study deals with the M1 Abrams tank, the methodology and procedures detailed may be applied to other systems with components that wear out.

20 Distribution Availability of Abstract ☒ unclassified unlimited ☐ same as report ☐ DTIC users	21 Abstract Security Classification Unclassified	
22a Name of Responsible Individual Lyn R. Whitaker	22b Telephone (include Area code) (408) 646-3482	22c Office Symbol 55Wh

Approved for public release; distribution is unlimited.

Analysis of Optimum Depot Level
Component Replacement Policy for
Retrograded M1 Abrams Tanks

by

John A. Wilhelm
CPT, U.S. Army
B.S., University of Nevada (Reno), 1981

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1990

Author: John A. Wilhelm

Approved by: Lyn R. Whitaker, Thesis Advisor

Michael G. Sovereign, Second Reader

Peter Purdue, Chairman,
Department of Operations Research

ABSTRACT

This study examines 48 M1 tank components for possible application of an optimum age replacement policy. The purpose is to support a broader study associated with the Reliability Centered - Inspect and Repair Only as Necessary (RC-IRON) program. The program provides depot level maintenance to tanks transferred or retrograded from Germany to the United States. An optimal age replacement policy reduces the number of failures while minimizing the cost associated with failure by replacing some older components before they fail. The component data for this analysis was drawn from the Field Exercise Data Collection (FEDC) at the National Training Center (NTC), Fort Irwin, California.

This thesis begins with a discussion of a methodology for determining an optimal replacement time. Distribution analysis is performed on component lifetimes as well as delay and repair times due to failure. The various costs associated with failure are estimated. The application of an age replacement policy was found to be beneficial for a few components and only when they had a high down-time cost. A graphical procedure is used to show sensitivity of the optimum policy to changes in cost. Component simulations are performed to pretest the results of a proposed maintenance policy. A six component system is simulated to demonstrate how the components could be tied together for later system level analysis. Although this study deals with the M1 Abrams tank, the methodology and procedures detailed may be applied to other systems with components that wear out.

INSPECTED 4

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification

By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

TABLE OF CONTENTS

I. INTRODUCTION 1

A. PROJECT 1

B. BACKGROUND 2

C. OBJECTIVE 2

D. MAINTENANCE POLICIES 3

II. METHODOLOGY FOR DETERMINING REPLACEMENT TIME 4

A. REQUIREMENTS 4

B. DISTRIBUTIONS APPROPRIATE FOR EARLY REPLACEMENT 4

C. PROCEDURE 7

III. FUNDAMENTAL DATA 10

A. AVAILABILITY 10

B. USER REPORTED 10

C. SAMPLE DATA COLLECTION 11

D. FIELD EXERCISE DATA COLLECTION 11

IV. SCREENING OF CANDIDATE COMPONENTS 13

A. STATISTICAL AND OPERATIONAL SIGNIFICANCE 13

B. RELIABILITY ANALYSIS OF THE COMPONENTS 15

V. COST ESTIMATION 18

A. MAINTENANCE COST 18

B. PENALITY COST FOR DOWN TIME 19

C. REPLACEMENT COST 21

D. DELAY AND REPAIR TIME DISTRIBUTIONS 23

VI. MAINTENANCE POLICY ANALYSIS 27

A. COMPONENT OPTIMAL REPLACEMENT MILEAGE 27

B. GRAPHICAL DETERMINATION OF REPLACEMENT INTERVAL . . 29

C. COMPONENT SIMULATION 32

D. TOWARDS SYSTEM LEVEL ANALYSIS AND SIMULATION 34

VII. CONCLUSIONS AND RECOMMENDATIONS 36

APPENDIX A. M1 SYSTEM DESCRIPTION 38

A. MISSION OF THE ABRAMS TANK 38

B. MODELS 38

1. M1 38

2. Improved M1 (IPM1) 38

3. M1A1 38

C. CAPABILITIES 38

1. Firepower 38

2. Mobility 39

3. Survivability . . . .

4. Communications . . . .

5. Maintenance 40

APPENDIX B. MAINTENANCE LEVELS 41

A. UNIT MAINTENANCE 41
B. INTERMEDIATE MAINTENANCE 41
C. DEPOT MAINTENANCE 41

APPENDIX C. RELIABILITY FITS 42
A. STARTER 42
B. TRANSMISSION 45
C. GRIP 48
D. NOZZLE 51
E. DISTBOX 54
F. LINK 57

APPENDIX D. DELAY FITS 60
A. STARTER 60
B. TRANSMISSION 64
C. GRIP 68
D. NOZZLE 72
E. DISTBOX 76
F. LINK 80

APPENDIX E. REPAIR TIME FITS 84
A. STARTER 84
B. LINK 88

APPENDIX F. PROGRAM USED TO DETERMINE AGE REPLACEMENT AND COST 92

APPENDIX G. SCALED TIME ON TEST PLOT PROCEDURE AND APL CODE 95

APPENDIX H. COMPONENT SIMULATION 98

APPENDIX I. SYSTEM SIMULATION 105

LIST OF REFERENCES 113

INITIAL DISTRIBUTION LIST 115

LIST OF TABLES

Table 1. REMAINING COMPONENTS 14

Table 2. DISTRIBUTION ANALYSIS RESULTS 17

Table 3. PART COST 19

Table 4. AVERAGE COST PER M1A1 1979-1991 20

Table 5. COST EQUATION INPUTS 22

Table 6. REPLACEMENT COST WITH STAND-BY PENALTY 22

Table 7. REPLACEMENT COST WITH FLOAT PENALTY 23

Table 8. OPTIMUM REPLACEMENT COST & MILEAGE WITH FLOAT PENALTY 29

Table 9. OPTIMUM REPLACEMENT COST & MILEAGE WITH STAND-BY PENALTY 29

Table 10. 20 YEAR STARTER SIMULATION RESULTS 33

Table 11. 20 YEAR LINK SIMULATION RESULTS 34

Table 12. 2 YEAR SIMULATION RESULTS, SIX COMPONENT SYSTEM . . . 35

LIST OF FIGURES

Figure 1. The Weibull Density Function f(t) with $E(X_i) = 2.0$ 6

Figure 2. The Failure Rate of The Weibull Distribution with $E(X_i) = 2.0$ 7

Figure 3. The Long Run Expected Average Cost Curves with $E(X_i) = 2.0$ 9

Figure 4. Starter Distribution Fit 16

Figure 5. Starter Percentile Plot 17

Figure 6. Histogram for Starter Delay 24

Figure 7. Cumulative Distribution for Starter Delay 25

Figure 8. Percentile Plot for Sarter Delay 26

Figure 9. Sample Cost Function for the Link with Stand-by Penalty 28

Figure 10. Starter & Grip Scaled Time on Test Plots 31

Figure 11. Link Scaled Time on Test Plot 32

Figure 12. Starter Distribution Fit 42

Figure 13. Starter Percentile Plot 43

Figure 14. Transmission Distribution Fit 45

Figure 15. Transmissionr Percentile Plot 46

Figure 16. Grip Distribution Fit 48

Figure 17. Grip Percentile Plot 49

Figure 18. Nozzle Distribution Fit 51

Figure 19. Nozzle Percentile Plot 52

Figure 20. Distbox Distribution Fit 54

Figure 21. Distbox Percentile Plot 55

Figure 22. Link Distribution Fit 57

Figure 23. Link Percentile Plot 58

Figure 24. Starter Delay Histogram 60
Figure 25. Starter Delay Distribution Fit 61
Figure 26. Starter Delay Percentile Plot 62
Figure 27. Transmission Delay Histogram 64
Figure 28. Transmission Delay Distribution Fit 65
Figure 29. Transmission Delay Percentile Plot 66
Figure 30. Grip Delay Histogram 68
Figure 31. Grip Delay Distribution Fit 69
Figure 32. Grip Delay Percentile Plot 70
Figure 33. Nozzle Delay Histogram 72
Figure 34. Nozzle Delay Distribution Fit 73
Figure 35. Nozzle Delay Percentile Plot 74
Figure 36. Distbox Delay Histogram 76
Figure 37. Distbox Delay Distribution Fit 77
Figure 38. Distbox Delay Percentile Plot 78
Figure 39. Link Delay Histogram 80
Figure 40. Link Delay Distribution Fit 81
Figure 41. Link Delay Percentile Plot 82
Figure 42. Starter Repair Histogram 84
Figure 43. Starter Repair Distribution Fit 85
Figure 44. Starter Repair Percentile Plot 86
Figure 45. Link Repair Histogram 88
Figure 46. Link Repair Distribution Fit 89
Figure 47. Link Repair Percentile Plot 90

THESIS DISCLAIMER

The reader is cautioned that all computer programs developed in this thesis research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of logic and computational errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

I. INTRODUCTION

A. PROJECT

The M1 Abrams Main Battle Tank is a centerpiece of the modern battlefield and may not be replaced for quite sometime. One of its orginal design features was that the components, not the entire system would be repaired at depot. The Army has indications that the burden of sustaining the tanks has grown as they have aged. Because of this growing maintenance the Army leadership would like to know if it is economical to use depots to identify a tank's condition and perform maintenance to extend serviceability.

The Deputy Chief of Staff for Logistics (DSLOG) tasked Headquarters, U.S. Army Materiel Command (HQ, AMC) to determine an optimal point in the life of the tank when a Reliability Centered - Inspect and Repair Only as Necessary (RC-IRON) program, should be applied and if the program can be improved. The life of a tank is measured in miles. Determining the optimal point for acceptance into the program is based upon operational conditions and economic analysis. The actual depot inspection and repair procedure has been established based upon previous programs. The overall viability of the program could be enhanced if improvements to the current depot implementation were found. HQ, AMC tasked Tank Automotive Command (TACOM) project management responsibility and U.S. Army Materiel Systems Analysis Activity (AMSAA) with analysis support. Descriptions are provided for the M1 tank in Appendix A and maintenance levels in Appendix B.

B. BACKGROUND

Analysis by TACOM and AMSAA will be conducted initially over the next two years. To enhance the analysis effort a basic hardware validation test was established. This test consists of transfering or retrograding 60 Improved M1 (IPM1) tanks from the 1st Infantry Division (Forward) in Germany to the National Training Center (NTC), Fort Irwin, California. At random, 14 of these tanks were selected and diverted to Anniston Army Depot, Anniston, Alabama, for RC-IRON, programmed to cost $95,000 per tank, before being delivered to the NTC as the sample group. The remaining 46 tanks were only subjected to standard deprocessing treatment. These tanks became the control group. The tanks arrived at the NTC in the first two months of 1990 and started to be used in exercises during the summer. The NTC was selected because the most mileage can be accumulated there and a data collection program is already in progress.

C. OBJECTIVE

The purpose of this study is to aid the RC-IRON project by focusing on the optimal age replacement policy for single components. A system level analysis is also breifly considered. There are 48 candidate components that AMSAA indicated were of prime interest. TACOM and AMSAA selected these parts because they are costly due to the high value of their cost per unit and the frequency of repair. In this thesis we will attempt to find an optimal maintenance policy for components among the suggested 48 for which such a policy makes sence. The methodology is defined in Chapter II. Data used to examine the 48 components is described in Chapter III. An initial screening of components is conducted in Chapter IV. Costs associated with this study are detailed in Chapter V. The components for which age replacement policies are appropriate, will be determined in Chapter IV. Based on the data in Chapter III and the costs from Chapter IV, optimum replacement mileages are estimated for the appropriate components in Chapter VI. Insights into system level analysis are also included in Chapter VI.

D. MAINTENANCE POLICIES

The ability of an armor unit to perform its mission is dependent on its tanks. A key factor is the quality of operation and availability which are primarily facilitated by maintenance. The two major types of maintenance are preventive and corrective. Corrective maintenance is performed by repair, replacement, or overhaul of equipment after it has failed. Often preventive maintenance is applied to extend service life or reduce the probability of failure [Ref. 1: p. 17]. Due to the possible economic and operational benefits, this study concentrates on planned preventive maintenance to reduce the probability of failure.

In particular, the preventative maintenance policy selected for study is the policy based on age (age replacement). This policy is implemented by making replacements either at the time of failure or after φ units of mileage. This is not to be confused with block replacement, where the policy is instituded by replacing a set of components in the tank at prescribed mileages $k\varphi$ ($k = 1, 2, \ldots$) independent of the history of failures in the tank system. The advantage of block replacement is that it is easier to implement due to a decreased administrative burden. Management of the policy is simplified when the incident mileage need not be recorded. However, components are replaced more frequently than needed, under a block replacement policy, thereby leading to increased cost [Ref. 2: p. 158]. Thus, this study will focus on age replacement policies. The optimal age replacement policy minimizes long run expected cost per mile with replacement at a certain mileage $\varphi^{\star}$. The methodology for determining this $\varphi^{\star}$ mileage is detailed in the next chapter.

II. METHODOLOGY FOR DETERMINING REPLACEMENT TIME

A. REQUIREMENTS

In order for preventative maintenance, under an age replacement policy, to be lucrative, the cost of an unscheduled replacement at failure must be higher than the cost of scheduled replacement. A description and estimate of these costs may be found in Chapter V with C_1 representing unscheduled and C_2 scheduled maintenance cost. It is also necessary that the component life distribution have a failure rate that increases with mileage [Ref. 3: p.46]. It would not make sense to replace an item that does not age or that is improving with age. To guard against choosing a replacement policy that actually increases costs by making replacements too frequently, the optimal maintenance policy is selected by minimizing the expected cost of repair per mile [Ref. 1: pp. 19-24].

B. DISTRIBUTIONS APPROPRIATE FOR EARLY REPLACEMENT

If a component is not expected to wear out it would be ridiculous to replace it before it fails. In other words, if it is improving with age, or staying the same, leave it alone. A class of distributions which captures a particular notion of aging is the Increasing Failure Rates (IFR) class of distributions i.e., those distributions with increasing failure rate [Ref. 2: p. 159]. Both Gamma and Weibull distributions are IFR when their shape parameter α is greater than one. The Weibull distribution is widely used for reliability analysis and is expected to be the most appropriate for this analysis. Gamma and other distribution can be examined in later analysis.

When the underlying lifetime distribution is a member of the two parameter Weibull family with shape parameter α and scale parameter λ , the density is given by

$$f(t) = \alpha \lambda (\lambda t)^{\alpha-1} e^{-(\lambda t)^{\alpha}} \qquad t > 0, \tag{2.1}$$

with failure rate

$$r(t) = \alpha \lambda (\lambda t)^{\alpha-1}, \qquad t \geq 0. \tag{2.2}$$

When $\alpha > 1.0$, the failure rate in Equation (2.2) is strictly increasing to infinity. As we will see, this property guarantees that a unique and finite optimal replacement age φ^* exists. The larger α is the more wear a component exhibits over time. Thus, α for greater than 1, the larger it is, the more appropriate it is for the component to be included in the application of our maintenance policy. Excluded from consideration is the exponential distribution, $\alpha = 1.0$, and Weibull distributions with decreasing failure rate ($\alpha < 1.0$). To give the reader a feel for the Weibull distributions used in this study, Figures 1 and 2 show densities and failure rates with different shape parameters. The distribution selected for illustration include, $\alpha = 1.2, 1.4, 1.6, 1.8, 2.0$. For comparison, the scale parameter λ is adjusted so that the expected lifetime is 2.0. In our analysis, lifetime is measured in miles, but we will use "time" and mileage interchangeably.

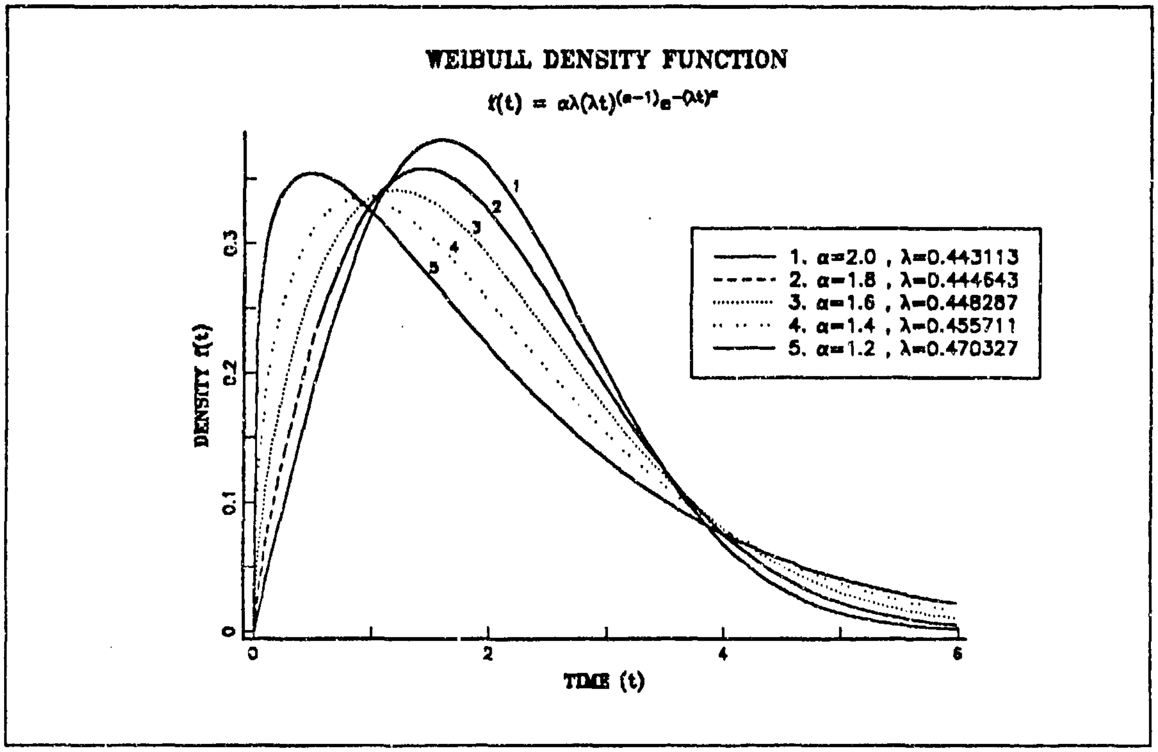

Figure 1. The Weibull Density Function f(t) with $E(X_i) = 2.0$

Source: Uyar, O. [Ref. 11]

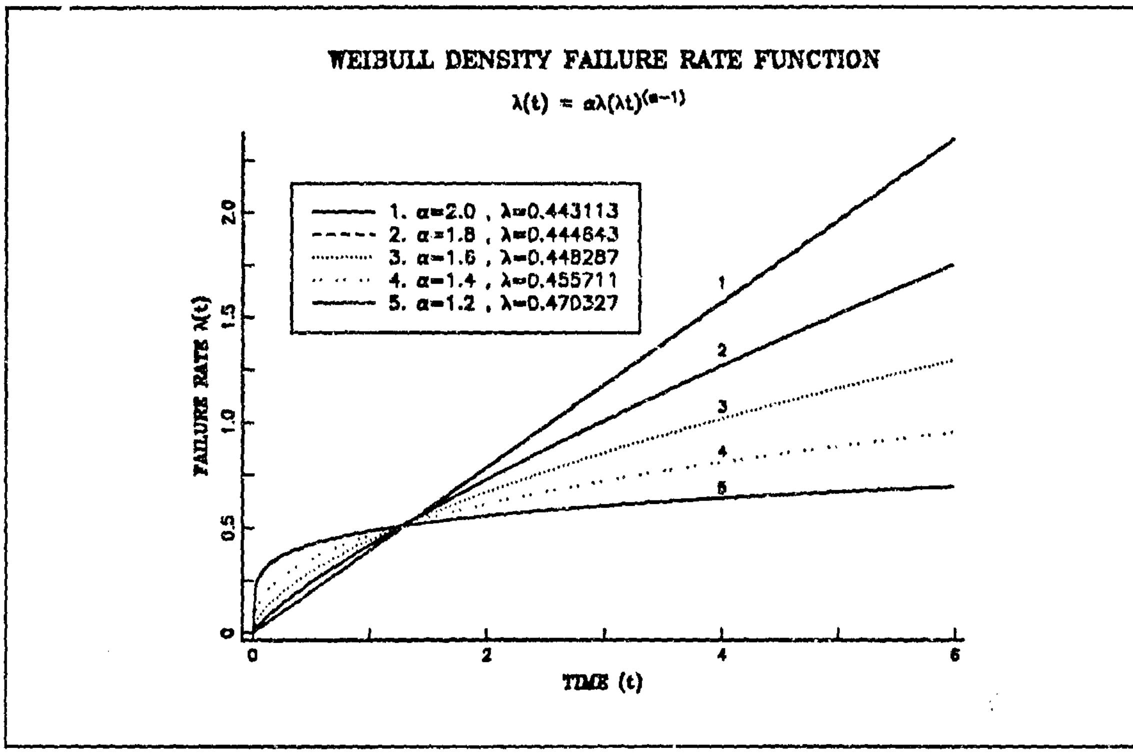

Figure 2. The Failure Rate of The Weibull Distribution with $E(X_i) = 2.0$

Source: Uyar, O. [Ref. 11]

C. PROCEDURE

A little background is now provided on the mechanics of finding an optimal replacement age. Under an age replacement policy, the time of planned replacement is specified as φ^* so that components are replaced at φ^* if they have not already failed. If the sequence of component lifetimes can be modeled as independent and identically distributed (iid) with distribution F, then the times between replacement form a renewal process. Thus, under such a policy with replacement at t, the long run expected cost per unit time C(t) can be determined from the following equations [Ref. 3: p. 87].

$$C(t) = \frac{C_1 \times F(t) + C_2 \times \overline{F}(t)}{\int_0^t \overline{F}(x)\,dx} \tag{2.3}$$

Where X has distribution F and $\overline{F} = 1 - F$ is the survival function. Note that C(t), in Equation (2.3) is the ratio of the expected cost of repairing one component and the expected time (mileage) between repair.

The Weibull survival function is given by

$$\overline{F}(t) = \begin{cases} e^{-(\lambda t)^{\alpha}}, & t > 0, \\ 1, & t \leq 0. \end{cases} \tag{2.4}$$

Inserting the survival function of Equation (2.4) above into Equation (2.3) leads to the long run cost function below.

$$C(t) = \frac{C_1\,(1 - e^{-(\lambda t)^{\alpha}}) + C_2\, e^{-(\lambda t)^{\alpha}}}{\int_0^t e^{-(\lambda x)^{\alpha}}\,dx}. \tag{2.5}$$

See Figure 3 for the cost function plotted using the five Weibull distributions depicted in Figure 1, with cost $C_1 = 5.0$ and $C_2 = 1.0$. It can be readily seen, especially at the higher shape parameters α, that C(t) indeed has a global minimum referred to as optimal age replacement time $\varphi^{\star}$. A proof that $\varphi^{\star}$ exists and is unique when the failure rate increases to infinity, as it does for Weibull distributions $\alpha > 1.0$, is given in [Ref. 2: pp. 161-168]. In Chapter VI, this formulation will be applied to component distributions to estimate $\varphi^{\star}$ to see at which mileage point, in the components life, it should be replaced. The component failure distributions will be estimated from the data described in the next chapter.

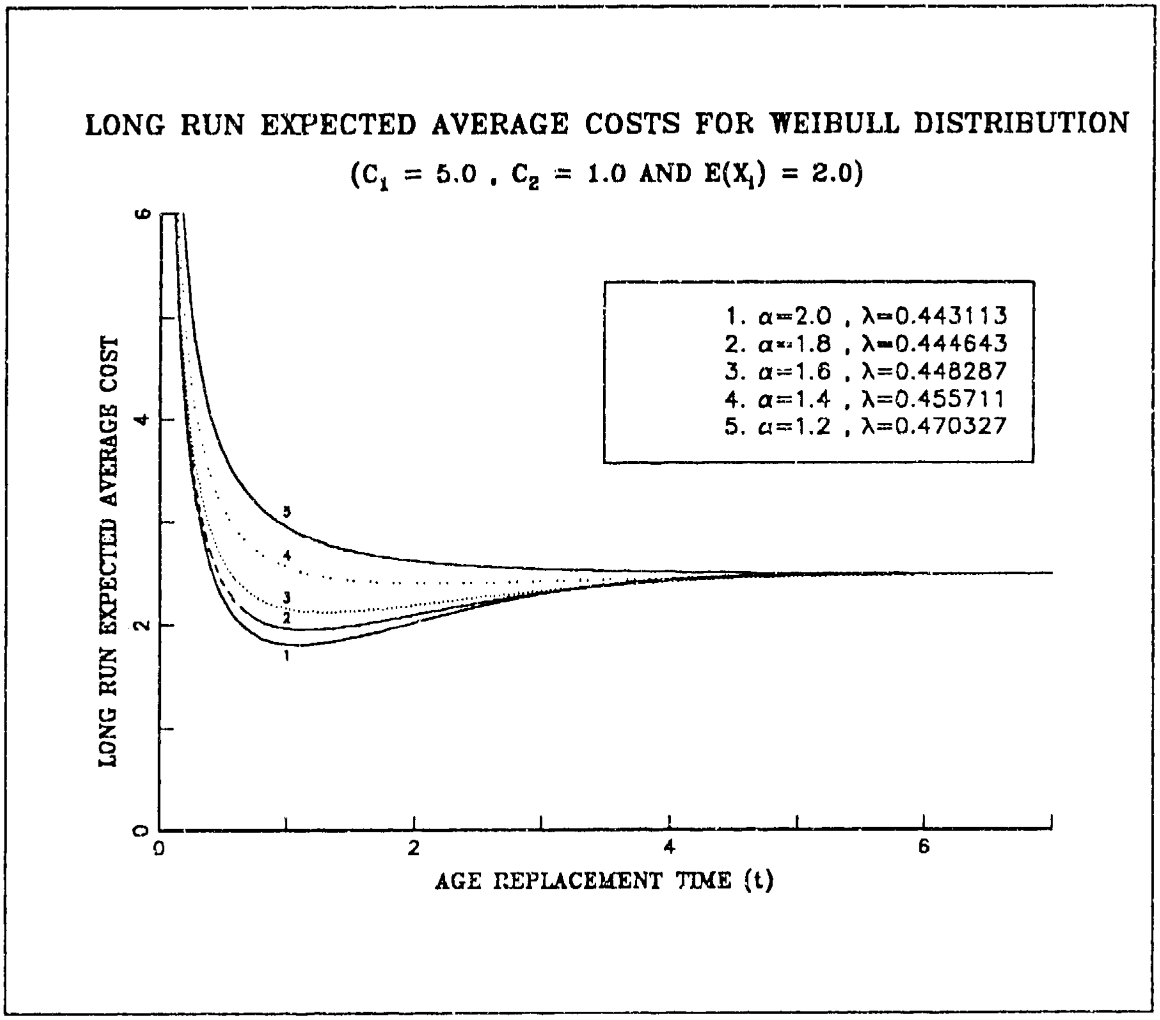

Figure 3. The Long Run Expected Average Cost Curves with $E(X_i) = 2.0$

Source: Uyar, O. [Ref. 11]

IV. SCREENING OF CANDIDATE COMPONENTS

A. STATISTICAL AND OPERATIONAL SIGNIFICANCE

Prior to any further analysis, components that had fewer than 20 failures were excluded. This eliminated those components in which fewer than 1/3 of the vehicles experienced a first time failure. They were excluded because the estimated probability distributions would be very suspect based on such small data sets.

One of the candidate components was the power pack that is actually made up of four modules. It was necessary to view each module seperately because of the different characteristics they have. Only the engine module of the four met the 20 failure minimum.

The tank track and road wheels were also eliminated from further consideration. These two items were identified in previous testing and use as having unacceptable wear. A contract was let in 1988 to produce a new track with a 300 percent increase in expected life. The following table is a list of those components that were not eliminated from the original 48 components by the above screening.

NOMENCLATURE	NAME	NSN
ENGINE STARTER, GAS	STARTER	2990-01-094-1377
		2990-01-136-1206
TRANSMISSION ASSEMBLY	TRANSMISSION	2520-01-157-3745
		2520-01-202-9865
GRIP ASSEMBLY, CONTR GUNNER'S	GRIP	1015-01-076-6865
		1015-01-076-6739
NOZZLE ASSEMBLY, FUEL	NOZZLE	2910-01-124-9325
		2910-01-214-2640
DISTRIBUTION BOX	DISTBOX	6110-01-169-5164
LINK ADJUSTING TRACK, RIGHT	LINK	2530-01-164-5805
TURRET NETWORKS BOX	TNBOX	1015-01-076-6688
ELECTRO-MECH FUEL	EMFUEL	2910-01-075-4926
		2910-01-080-9132
PUMP, FUEL ELECTRICAL	EPUMP	2910-01-083-3153
		2910-01-232-9687
ELECTRONIC CONTROL ASSEMBLY	ECASMBLY	2590-01-154-6656
HUB, WHEEL ASSEMBLY	HUB	2530-01-063-5666
SPROKET WHEEL	SPROKET	3020-01-065-6209
PUMP UNIT, ROTARY	RPUMP	4320-01-073-4829
POWER CONTROL UNIT	PCU	1240-01-204-5765
		1240-01-074-8969
		1240-01-162-0367
SIGHT, GUNNER'S PRIMARY	SIGHT	1240-01-132-1693
		1240-01-152-5344
THERMAL RECIVER UNIT	THERMALREC	1240-01-074-8947
IMAGE CONTROL UNIT	ICU	1240-01-246-1872
		1240-01-074-8946
LASER RANGE FINDER	LASERRF	1240-01-149-8302
TURBINE ENGINE	ENGINE	2835-01-120-3674
		2835-01-216-8639

Table 1. REMAINING COMPONENTS

B. RELIABILITY ANALYSIS OF THE COMPONENTS

In Chapter III, recall that all the failures were recorded as interval censored or right censored data. For each of the components, failure distributions were fit nonparametrically and parametrically. See Figure 3 for an example. The sample nonparametric cumulative distribution function is a step function which is calculated using Turnbull's nonparametric maximum likelihood estimator based on right and interval censored data [Ref. 4 pp. 169-173]. Such a procedure distributes probability among the censoring intervals and to the right of the largest censoring interval when the largest observation is right censored. The data was also fit parametrically to a Weibull distribution using the method of maximum likelihood. The fits were generally quite good, see Figure 5 supporting the Figure 4 example. The outliers that have low mileage and relatively high percentiles may be explained under the phenomina of infant mortality. All the significant and appropriate component distributional fits and percentile plots, along with a table of parameters estimates and standard errors are detailed in Appendix C. A summary of these that have increasing failure rate indicated by the estimated shape parameter $\hat{\alpha} > 1.0$ is given in Table 2.

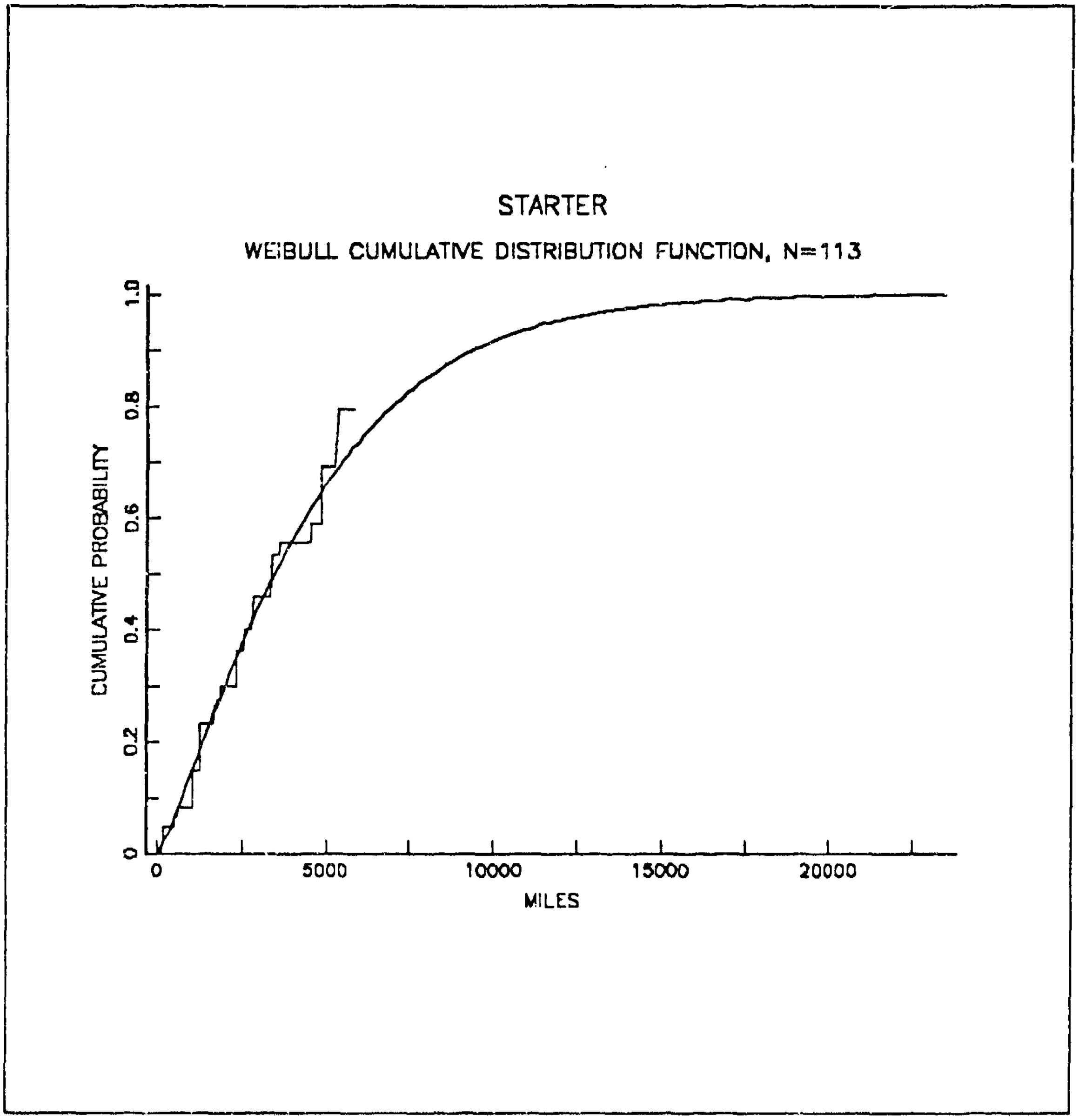

Figure 4. Starter Distribution Fit

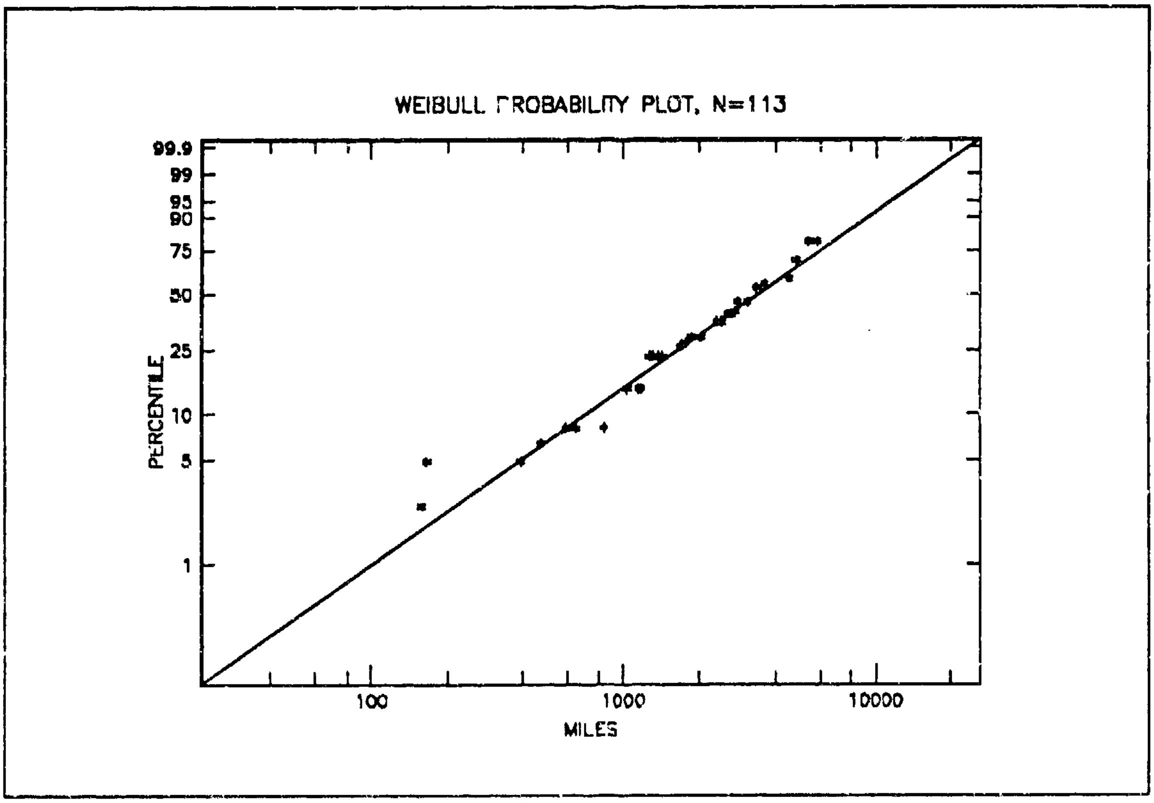

Figure 5. Starter Percentile Plot

PART	SHAPE α	SCALE $\beta = 1/\lambda$	NUMBER OF FAILURES
STARTER	1.1999	4689.76.	57
TRANSMISSION	1.4455	7479.5	29
GRIP	1.5539	4369.9	54
NOZZLE	1.3384	4438.72.	56
DISTBOX	1.5315	6858.6	32
LINK	1.2801	10239.0	22

Table 2. DISTRIBUTION ANALYSIS RESULTS

V. COST ESTIMATION

A. MAINTENANCE COST

In analysis of this type, cost is a major factor in the evaluation process. To compute an optimal replacement interval the unscheduled and scheduled maintenance cost must be estimated. Generally the maintenance cost (COM) may be calculated using the breakdown provided in [Ref. 5: p. 383].

$$COM = (C_{omm} + C_{omx} + C_{oms} + C_{omt} + C_{omp} + C_{omf} + C_{omp}) \tag{5.1}$$

with

C_{omm} = Maintenance Personnel and Support Cost

C_{omx} = Cost of Repair Parts

C_{oms} = Test and Support Equipment Cost

C_{omt} = Transportation and Handling Cost

C_{omf} = Cost of Maintenance Facilities

C_{omd} = Cost of Technical Data

For this maintenance policy study, the cost of maintenance will be calculated based upon maintenance personnel and parts cost only. The other costs are assumed to be either negligible, compared to other uncertainties, or not relevant, or possibly sunk, for this analysis. The maintenance facilities and test equipment have already been purchased and are considered sunk cost. The transportation and data collection costs are difficult to ascertain at this time and should play a minor role in a component replacement policy. This will not be true in the system level analysis, since these costs, especially the transportation cost, will play a significant role. The labor rates were computed to be $104/hr in the field and $175/hr at depot by the author [Ref. 6: p. 23] and myself. These figures were crudely calculated to obtain a feel for the labor cost and may be too high. We used figures from the base line cost estimate, maintenance allocation chart, and RC-IRON estimate cost to calculate these man-hour costs. In this study, it is assumed that the labor rate is $50/hr for both locations. This is a standard labor rate for many civilian repair shops in areas of the United States. The parts cost Table 3 were obtained from the current Army Master Data File.

PART	COST (DOLLARS)
STARTER	$ 794.00
TRANSMISSION	$ 139,998.00
GRIP	$ 1,955.00
NOZZLE	$ 944.00
DIST BOX	$ 12,021.00
LINK	$ 488.00

Table 3. PART COST

B. PENALITY COST FOR DOWN TIME

In private industry the cost of down-time is found by estimating the cost of lost revenue. The military does not have a profit motive to fall back on. In this study two different levels of penalties will be developed for management consideration. They are the stand-by and float penalties, named after two possible Army actions. The first penalty, float, is named after the Operational Readiness Float (ORF) which is designed to improve the readiness of combat units. Extra combat systems, float tanks, are kept at an intermediate support maintenance unit for exchange with a customer whose tank cannot be repaired in a specified time. The second and larger penalty cost is stand-by. This penalty is for a tank which is standing by and ready to go in the event one of a unit's tanks fail prior to going on a critical mission. The penalties are recorded in dollars and are based upon system costs. This will enable us to use them in conjunction with actual maintenance cost to determine the unscheduled and scheduled maintenance cost. The acquisition cost of the tank varies from year to year, for this study $3,000,000 will be used. This was based upon the cost for M1A1's from [Ref. 7: p. 32] Table 4, principally the 1990 figure.

YEAR	COST PER TANK
1979	$ 3,390,000.00
1984	$ 2,047,000.00
1990	$ 2,977,000.00
1991	$ 3,552,000.00

Table 4. AVERAGE COST PER M1A1 1979-1991

In the Abrams Base Line Cost Estimate [Ref. 8] the average annual sustainment cost tank for the IPM1 is $562,500 and M1A1 is $514,900. For analysis purposes we shall use $500,000. The Army has issued a life cycle estimate of 20 years for planning purposes. Using the 20 year life cycle and average annual sustainment cost the sustainment cost f the M1 will be $10,000,000 over its lifetime.

The lower of the two penalties is the float. It is based upon the ORF action and calculated system aquisition cost, neglecting the sustainment cost of the float vehicle. The actual ORF cost would be higher because some sustainment cost would be incurred.

$$\begin{aligned} \textit{Downtime Cost Per Day} &= \left(\frac{\textit{Down Time in Days}}{365\ \textit{Days}}\right)\left(\frac{\textit{Aquisition Cost}}{20\ \textit{Year Life Cycle Cost}}\right) \\ \textit{Downtime Cost} &= (\textit{Downtime in Days})\left(\frac{\$\,411.}{\textit{Day}}\right) \qquad (5.2) \\ \textit{Float Penalty Cost Day} &= \frac{\$\,411.}{\textit{Day}} \end{aligned}$$

Stand-by is the larger penalty. The tank it represents is standing by and cost are calculated proportionate to aquisition and sustainment cost. The annual cost of the crew which would realistically also have to be standing by is not included [Ref. 6: p. 22].

$$
\begin{aligned}
\textit{Downtime Cost Per Day} &= \left(\frac{\textit{Down Time in Days}}{365\ \textit{Days}}\right)\left(\frac{\textit{Aquisition} + \textit{Sustainment Cost}}{20\ \textit{Year Life Cycle Cost}}\right) \\
\textit{Downtime Cost} &= (\textit{Downtime in Days})\left(\frac{\$\,1{,}781.}{\textit{Day}}\right) \qquad (5.3) \\
\textit{Stand-by Penalty Cost Day} &= \frac{\$\,1{,}781.}{\textit{Day}}
\end{aligned}
$$

C. REPLACEMENT COST

If under an age replacement policy, a component is to be replaced before it fails, the cost of failure must be higher than the cost of scheduled replacement. The cost of failure can be in the form of cost, danger, or lost time. These costs will be refered to as C_1 for all unscheduled and C_2 for scheduled maintenance. The costs are calculated with the following linear relationships.

$$
\begin{aligned}
C_1 &= a(MTD) + b \\
C_2 &= a(MTTR) + b
\end{aligned}
\qquad (5.4)
$$

with

a = Penalty Cost Per Day

MTD = Mean Downtime due to Delay in Days

MTTR = Mean Time to Repair in Days

b = Part Cost + Labor

Labor = $\left(\frac{Cost}{Manhour}\right)$ x (MTTR)

The values used to compute C_1 and C_2 in Equation (5.4) are given in Table 5. MTTR figures in man hours were provided by [Ref. 6: pp. J2-3]. It is assumed that although the MTTR times are often for two mechanics, these times are representative of the delay for scheduled maintenance. MTTR was converted from hours to days for standardization. The labor cost in representative of the $50 per hour labor rate times MTTR. The labor rate and parts cost were detailed in Section B of this chapter. The replacement cost calculated with both pentalty type are in Table 6. The table also includes the cost ratio $-\frac{C_2}{(C_1 - C_2)}$ needed in the next chapter for the graphical replacement interval section. The MDT for each component in days was obtained from fitted mean calculated in Section D and represents the unscheduled delay.

PART	MTD (DAYS)	MTTR (MNHRS)	MTTR (DAYS)	LABOR ($)	b ($)
STARTER	.76	2.0	.08	$ 100.	$ 894.
TRANS-MISSION	1.34	6.6	.28	$ 330.	$ 140,328.
GRIP	.81	1.3	.05	$ 65.	$ 2,020.
NOZZLE	.63	7.8	.33	$ 390.	$ 1,334.
DISTBOX	.87	1.8	.08	$ 90.	$ 12,111.
LINK	1.40	2.8	.12	$ 140.	$ 628.

Table 5. COST EQUATION INPUTS

PART	C_1	C_2	COST RATIO
STARTER	$ 2,248.	$ 1,036.	- .85
TRANSMISSION	$ 142,715.	$ 140,826.	-74.55
GRIP	$ 3,462.	$ 2,109.	-1.56
NOZZLE	$ 2,456.	$ 1,922.	-3.60
DISTBOX	$ 13,660.	$ 12,253.	-8.71
LINK	$ 3,121.	$ 842.	-.37

Table 6. REPLACEMENT COST WITH STAND-BY PENALTY

PART	C_1	C_2	COST RATIO
STARTER	\$ 1,206.	\$ 927.	- 3.32
TRANSMISSION	\$ 140,879.	\$ 140,443.	-322.12
GRIP	\$ 2,353.	\$ 2,041.	-6.54
NOZZLE	\$ 1,593.	\$ 1,470.	-11.95
DISTBOX	\$ 12,469.	\$ 12,141.	-37.37
LINK	\$ 1,203.	\$ 677.	-1.29

Table 7. REPLACEMENT COST WITH FLOAT PENALTY

D. DELAY AND REPAIR TIME DISTRIBUTIONS

Distributions were fit to delay and repair times. Results from this analysis were used in Section C, to compute maintenance cost for some components. These costs in conjunction with the estimated component failure distribution are used in estimating optimal replacement mileage in Chapter VI. This analysis may indicate that additional components should be eliminated from further policy consideration. The results of this section will also be used in the simulations in Chapter VI.

The six delay and two repair data sets for the remaining candidate component were fitted to the lognormal distribution. The lognormal distribution was chosen because it seemed to model delay and repair times. Most but not all fits were good. It was decided to stay with this model for these time distributions because of the way the data was collected. It is human nature to use rounded time increments, such as a fraction of a day. In the following example (starter), the bulk of observations are at a half a day. Figures 6, 7, and 8 are examples of the histogram,

cumulative probability plot, and percentive plot for delay times. The three plots and analysis table information for the six components are contained in Appendix D.

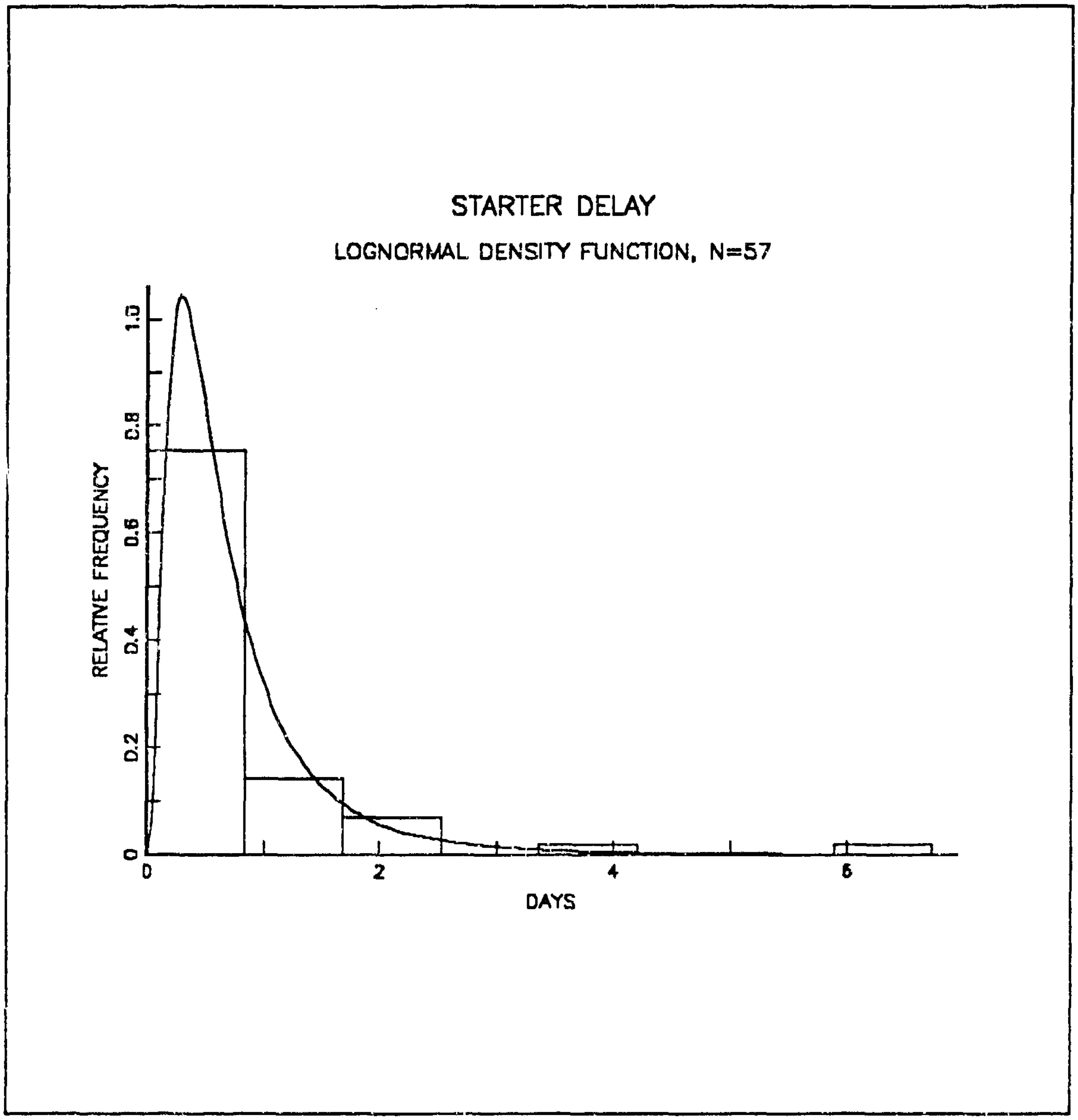

Figure 6. Histogram for Starter Delay

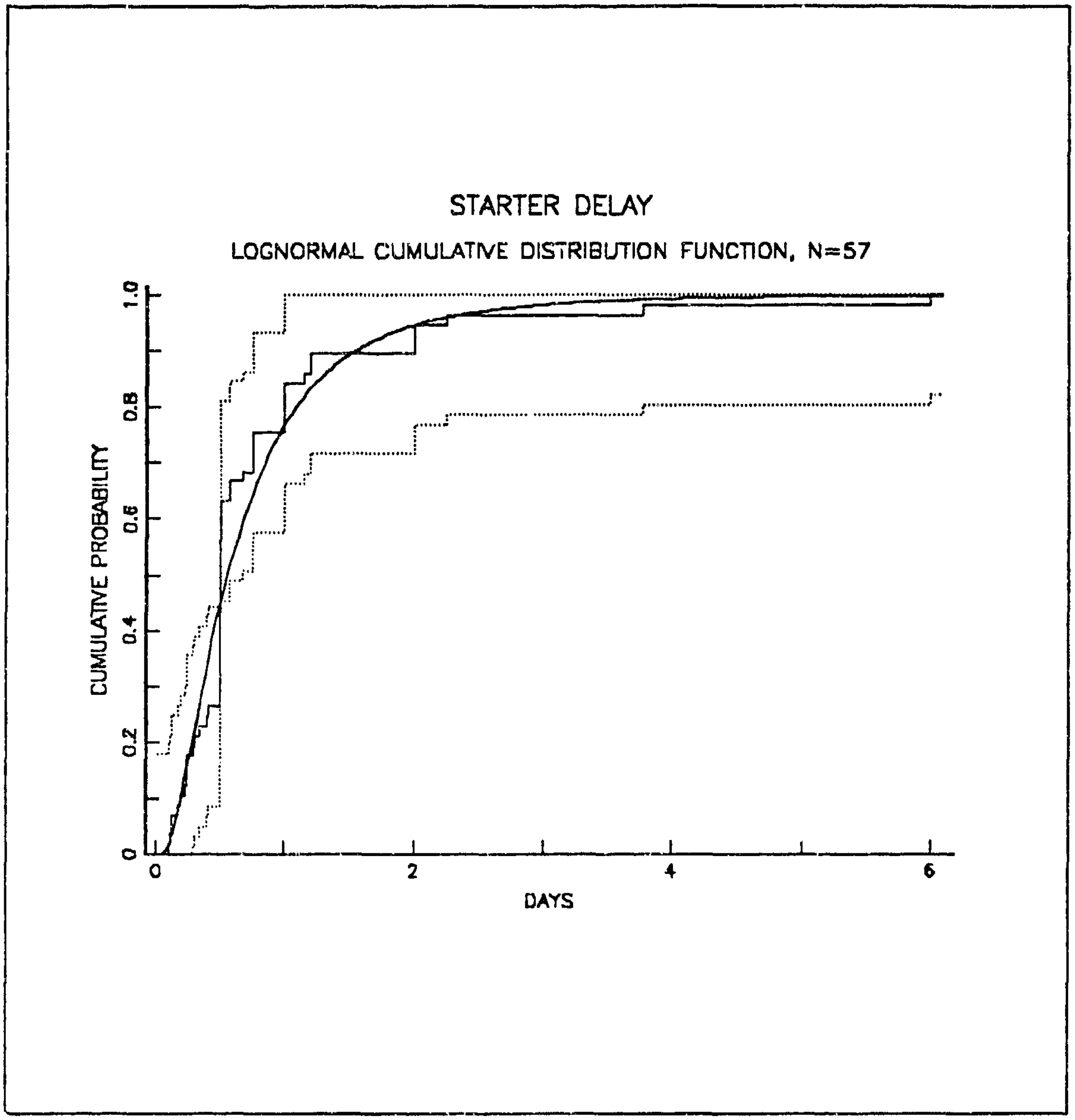

Figure 7. Cumulative Distribution for Starter Delay

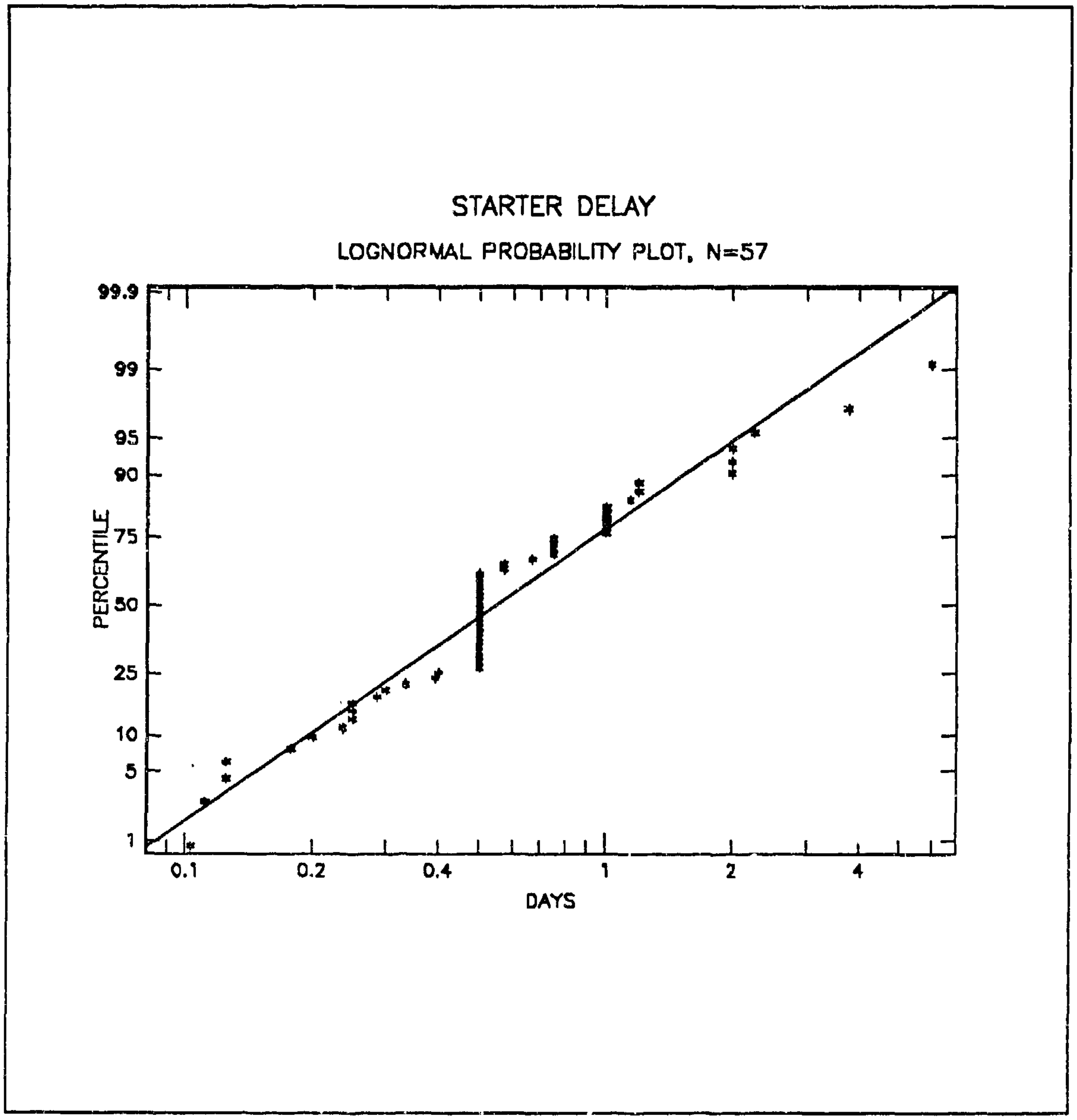

Figure 8. Percentile Plot for Sarter Delay

The repair fits were made for two components for latter simulation use. These fits with their graphical counter parts to the above Figures are located in Appendix E.

VI. MAINTENANCE POLICY ANALYSIS

A. COMPONENT OPTIMAL REPLACEMENT MILEAGE

The component failure distributions of Chapter IV and cost results of Chapter V are now applied to Equation (2.3). This is accomplished by using the APL program in Appendix F. The cost function C(t) was estimated by using simulation. This was accomplished by using 8,000 pseudo random lifetimes, generated from a Weibull distribution with parameters estimated from the component data described in Chapter III. The simulated C(t) is within $.01 of the actual C(t). As an example, the cost function C(t), based on 1,000 pseudo random numbers, is plotted (Figure 9). The optimum replacement milage and coresponding minimum cost per mile were found for each component by minimizing the simulated cost function. These results are located in Table 8 and 9. Under the smaller float penalty no components are recommended for age replacement. If the higher stand-by penalty is adopted, the only components that are recommended for early replacement are the link, starter, and grip. The starter and grip are marginally recommended, because their replacement points are near the end of their useful lifes. It should also be noted that the replacement mileage should be rounded up as long as the optimal cost is not changed significantly. This is due to the very large cost of replacing the component too early versus the relatively smaller increases in cost if it is replaced to late.

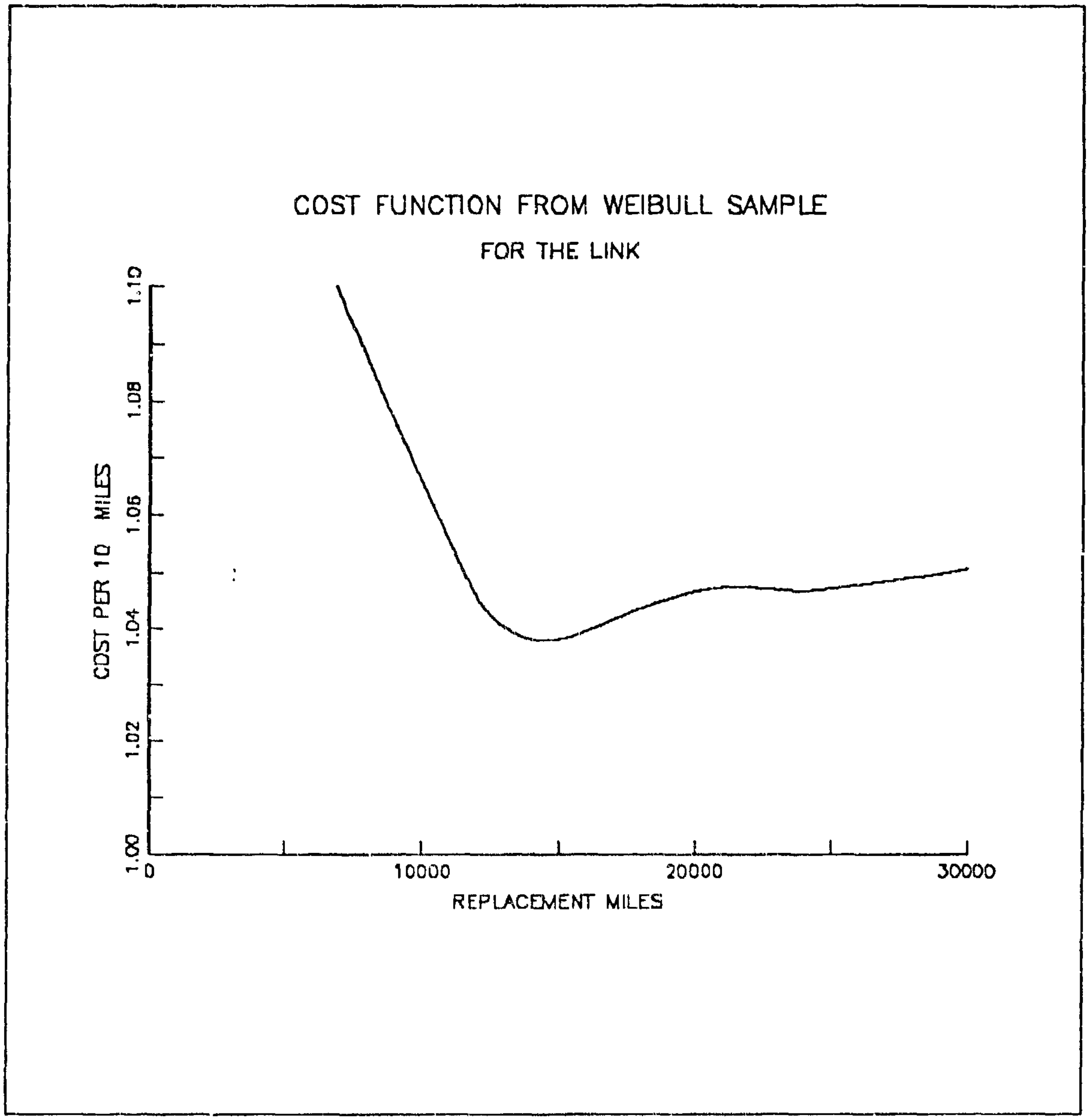

Figure 9. Sample Cost Function for the Link with Stand-by Penalty

PART	COST PER 100 MILES	REPLACEMENT MILEAGE	MAXIMUM LIFE (MILES)
STARTER	$ 1.36	19,668.	20,000.
TRANSMISSION	$ 82.92	25,000.	25,000.
GRIP	$ 5.05	11,972.	12,000.
NOZZLE	$ 2.45	15,974.	16,000.
DISTBOX	$ 10.13	20,000.	20,000.
LINK	$ 4.29	29,921.	30,000.

Table 8. OPTIMUM REPLACEMENT COST & MILEAGE WITH FLOAT PENALTY

PART	COST PER 100 MILES	REPLACEMENT MILEAGE	MAXIMUM LIFE (MILES)
STARTER	$ 2.56	18,865.	20,000.
TRANSMISSION	$ 84.61	25,000.	25,000.
GRIP	$ 7.31	10,000.	12,000.
NOZZLE	$ 3.75	15,842.	16,000.
DISTBOX	$ 11.17	19,985.	20,000.
LINK	$ 10.07	16,384.	30,000.

Table 9. OPTIMUM REPLACEMENT COST & MILEAGE WITH STAND-BY PENALTY

B. GRAPHICAL DETERMINATION OF REPLACEMENT INTERVAL

The determination of the optimal replacement mileage can also be made graphically. The method which uses a scaled total time on test plot is described in [Ref. 1: pp. 113-116] by Barlow. The main advantage to this procedure is that sensitivity to changes in cost is readily apparent. Another important feature is that other cost ratios may be analyzed very quickly. We will use this method on the components recommended for the application of a replacement policy in the previous section. For these components a scaled time on test plot is given in Figures 11, 12, and 13. The costs ratio are obtained in Chapter V. The procedure for obtaining the scaled time on test plot may be found in Appendix G along with an APL program for assistance. To read the plot, a line is drawn from the cost ratio $-\frac{C_2}{(C_1 - C_2)}$ on the horizontal axis to the tangency point on the time on test curve. From the tangency point one may vertically drop down and read the value of the cumulative failure distribution evaluated at the optimum replacement milage. The optimal replacement mileage may then be read from the plot of the cumulative distribution in Chapter VI and Appendix C.

If the scaled time on test function is rather flat in the vicinity of the tangency point, then the optimum is not sensitive to small changes in the cost ratio. If a new cost ratio is of interest, then a new line may be drawn which is tangent to the total time on test function to find a new optimum. Now we have the convenience of not having to perform more calculations or rerunning programs for different costs.

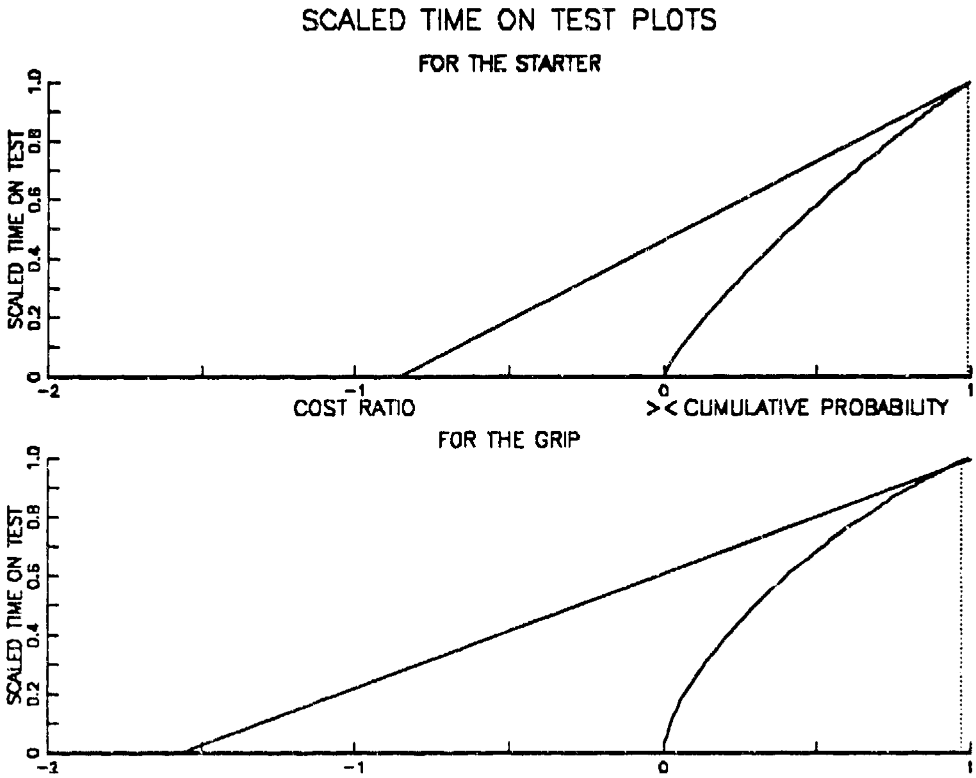

Figure 10. Starter & Grip Scaled Time on Test Plots

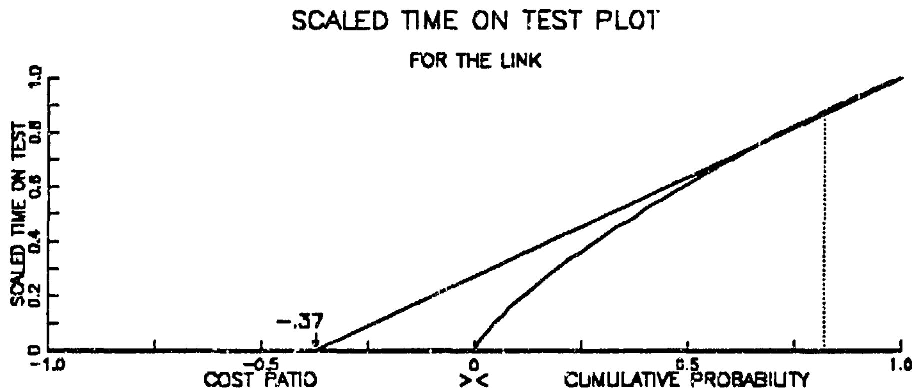

Figure 11. Link Scaled Time on Test Plot

C. COMPONENT SIMULATION

The operation of the link and starter will now be simulated individually to pretest the results of the proposed maintenance policies. Previously gathered information was used as inputs to the simulation. Since the main data set in this analysis was from the NTC and that is where the tanks are going to, we will use the NTC operating tempo for accumulated mileage. That is, the functioning components will accumulate mileage at rate equivalent to an average NTC tank with no other component induced down time. The actual program was coded in SIMSCRIPT II.5 using discrete-event methodology represented by the process in Appendix H. The simulations were run for two year and twenty year intervals for 5,000 repetitions a piece. In the simulation, tanks are retrograted after two years and the life cycle of a tank is taken to be twenty years. Resulting failures, cost, and availability for 20 year runs are located in Table 8 along with their deviations. No parts were replaced for either component in the two year runs. The starter had 156 parts preventatively replaced or approximately 3% of the tanks had the policy applied during their lifetime. A larger number occured for the link 4270 or 85% experienced preventative replacements during a life cycle.

The performance of the maintenance policies could be improved some, by not allowing replacements to occur towards the very end of the 20 year life cycle. This would serve to reduce some of the maintenance cost where the full benefits would not be realized. This simulation is a specialized version, with more component statistics taken, of the program discussed in the next section. The comments for either program apply to the other. Verification will be discussed in the next section.

	WITH OUT POLICY	WITH POLICY
NUMBER FAILED		
AVERAGE	10.72	10.70
STANDARD DEVIATION	2.82	2.83
REPAIR COST		
AVERAGE	$ 8,807.	$ 8,821.
STANDARD DEVIATION	$ 2,318.	$ 2,298.
PENALTY COST		
AVERAGE	$ 11,423.	$ 11.441.
STANDARD DEVIATION	$ 5,591.	$ 5,582.
TOTAL COST		
AVERAGE	$ 20,229.	$ 20,261.
STANDARD DEVIATION	$ 7,146.	$ 7,116.
PERCENT AVAILABILITY	99.9121	99.9120

Table 10. 20 YEAR STARTER SIMULATION RESULTS

	WITH OUT POLICY	WITH POLICY
NUMBER FAILED		
AVERAGE	4.79	4.54
STANDARD DEVIATION	1.76	1.90
REPAIR COST		
AVERAGE	$ 2,567.	$ 2,891.
STANDARD DEVIATION	$ 947.	$ 815.
PENALTY COST		
AVERAGE	$ 3,086.	$ 2,973.
STANDARD DEVIATION	$ 4,463.	$ 4,395.
TOTAL COST		
AVERAGE	$ 5,652.	$ 5,863.
STANDARD DEVIATION	$ 4,779.	$ 4,681.
PERCENT AVAILABILITY	99.9762	99.7771

Table 11. 20 YEAR LINK SIMULATION RESULTS

D. TOWARDS SYSTEM LEVEL ANALYSIS AND SIMULATION

Over the next two years data is going to be collected on the RC-IRON tanks and control group. Key components like the 48 candidates could be tabulated separately, aggregating the maintenance data for the remaining components. The aggregated failures could be treated as a single component or as several components treated by catagory. These notional components could be analized using the techniques of this study. Because only components are renewed and not the system, simulation may be the way to explore alternatives. As an example of how this might work we shall take the six components who exibited increasing failure rates and bring them together as an operating system. The program, Appendix I, is similar to the component simulation of the previous section. The difference is that we now have multiple components and a new process has been introduced to tie them together as a system.

A partial verification of this program was accomplished using queing theory. Five components were used in this test. Failures for each component were modeled as a special case of the Wiebull distribution, the Exponential, with mean failure time equal to five days. By chosing the Exponential distribution and keeping the repair times small, also Exponential with mean equal to 2.4 hours or 1/10 day, we expect the results to resemble a M/M/1 queue. This is because we have a Poisson arrival process and because when all components are stopped when one fails we have a single server. The long run expected availability of the server is 90%. The simulated availability is 90.8% after 1,000 repetitions. This shows that the simulation is working properly.

The six component simulation was run 500 times. The results for mileage, number failures, and down time are located in Table 9.

	AVERAGE	STANDARD DEVIATION
MILEAGE	4758	10.49
DOWN TIME (DAYS)	1.51	1.41
NUMBER OF FAILURES	4.07	1.74

Table 12. 2 YEAR SIMULATION RESULTS, SIX COMPONENT SYSTEM

VII. CONCLUSIONS AND RECOMMENDATIONS

An age replacement policy is not recommended for inclusion in the RC-IRON program based upon the 48 component NTC data set. As the program is currently established, the tanks in Germany would not have accumulated enough mileage for the three identified components (starter, grip, and link) to be replaced. There is a chance that the overall results may change if the Germany SDC data is analyzed. The environment of operation is different in Germany than at NTC so the components may exhibit different life distributions. If the Army leadership was to assign more value to availability than even the stand-by penalty, components may merit replacement. If the components were to be replaced in the field under an age replacement policy for the entire life cycle of the tank, the link would be the only contender. It should be noted that the assumptions of this study should be reexamined even for this component. This should be done from a engineering stand point. The link is used in conjuction with the tank track, so other factors may explain its failure distribution. Even with no parts being recommended for this type of replacement policy, this study should be of value. The life distributions have been examined and the components may be ranked in several ways. This may provide input into the inspection process, in that components which merit increased attention have been identified. A nonparametric analysis along the lines of this thesis would be beneficial if the orginal NTC data set of time on test was expanded.

A more general problem is the problem of determining which tanks should be subjected to RC-IRON. By simulating the tanks operation with components of interest, a near optimum solution for the mileage of RC-IRON application may be determined. This simulation could use the techniques and information of this study. It will also require the analysis of SDC Germany data and future NTC Hardware Test results. This system simulation may be built upon the simplistic simulation of the previous chapter.

APPENDIX A. M1 SYSTEM DESCRIPTION

A. MISSION OF THE ABRAMS TANK

The mission of the Abrams tank system is to close with and destroy enemy forces by use of firepower, maneuver and shock effect. The Abrams tank, organic to armored battalions and armored cavalry squadrons, will normally operate as part of combined arms team of armor, infantry and artillery to accomplish this mission. [Ref. 9: p.2]

B. MODELS

1. M1

This is the basic model of the tank. Chrysler Corporation was awarded Full Scale Engineering Development in 1976 and sold its tank building subsidiary to General Dynamics in 1982. By 1985, the end of production, 2,374 were made.

2. Improved M1 (IPM1)

This is an M1 with improved armour protection. A total of 894 were built from 1984 to 1986.

3. M1A1

A number of improvements were made to the IPM1 for this tank. These include: gun (see firepower next section), crew environment control, suspension, and transmission. Deliveries of this tank began in 1987 and are scheduled through 1991. By the end of 1989, 2,330 had been produced. [Ref. 10: pp.742-751]

C. CAPABILITIES

1. Firepower

The M1 version of the Abrams tank is armed with a 105 millimeter rifled cannon, the L68. This cannon is combat-proven and arms the tanks of many allies. The

M1A1 version, which entered production in 1985, is armed with the M256 120 millimeter smoothbore cannon, an improvement of the German 120mm cannon. Equipped with the M829 armor-piercing, fin-stabilized, discarding sabot round, this cannon can penetrate any known main-battle tank armor currently fielded. A multipurpose high-explosive anti-tank round is also carried. A digital fire control computer, coupled with a laser range finder, thermal sights and a turret stabilization system enable the Abrams to engage targets under all weather conditions and on the move. The tank is also armed with a .50 caliber commander's machinegun and two 7.62 mm machineguns.

2. Mobility

The Abrams was the worlds' first fielded tank to be equipped with a gas turbine engine. This engine develops 1500 horsepower and is coupled to a hydraulic transmission. An advanced suspension system featuring rotary shock absorbers enables the Abrams to operate at a maximum governed cross-country speed of 42 miles per hour.

3. Survivability

The highest priority in the design of the Abrams was the protection of the crew. Compartmentation of fuel and ammunition, nuclear/chemical/biological protection and halon fire suppression systems have been incorporated. Improved armor, responsive speed and agility, grenade and engine smoke generators and a low silhouette all contribute to the survivability of the system.

4. Communications

Crew intercommunications are provided by the AN/VIC-1 intercom system. Tactical radio communications are provided by the AN/VRC-12 family of radios, with a maximum two net capability. Provisions are being made for the additions of position navigation and digital communication in future models.

5. Maintenance

Maintenance considerations played a key part in the design of the Abrams. Ease of power pack removal and installation is the primary example. Additionally, most other major components are designed for easy removal and installation after fault isolation by built-in test equipment (BITE) or by the standard test equipment-M1 (STE-M1). [Ref. 9: p.3]

APPENDIX B. MAINTENANCE LEVELS

A. UNIT MAINTENANCE

This is the lowest level, it includes maintenance task performed by operator, crew, and unit personnel. It may be equated to the maintenance performed by the owner of a car and service station. Preventive checks and services to detect potential problem is a key component. Replacements are limited to small components which are quickly and easily replaced.

B. INTERMEDIATE MAINTENANCE

Entire units are devoted to this level of maintenance. The intermediate is further divided into direct support and general support. Direct support is provided on a repair and return basis to units that experience failures beyond their capability to repair. General support units rebuild components in support of the Army supply system.

C. DEPOT MAINTENANCE

This is the highest level and is performed at large fixed depot facilities. They provide rebuild and overhaul for both systems and components.

APPENDIX C. RELIABILITY FITS

A. STARTER

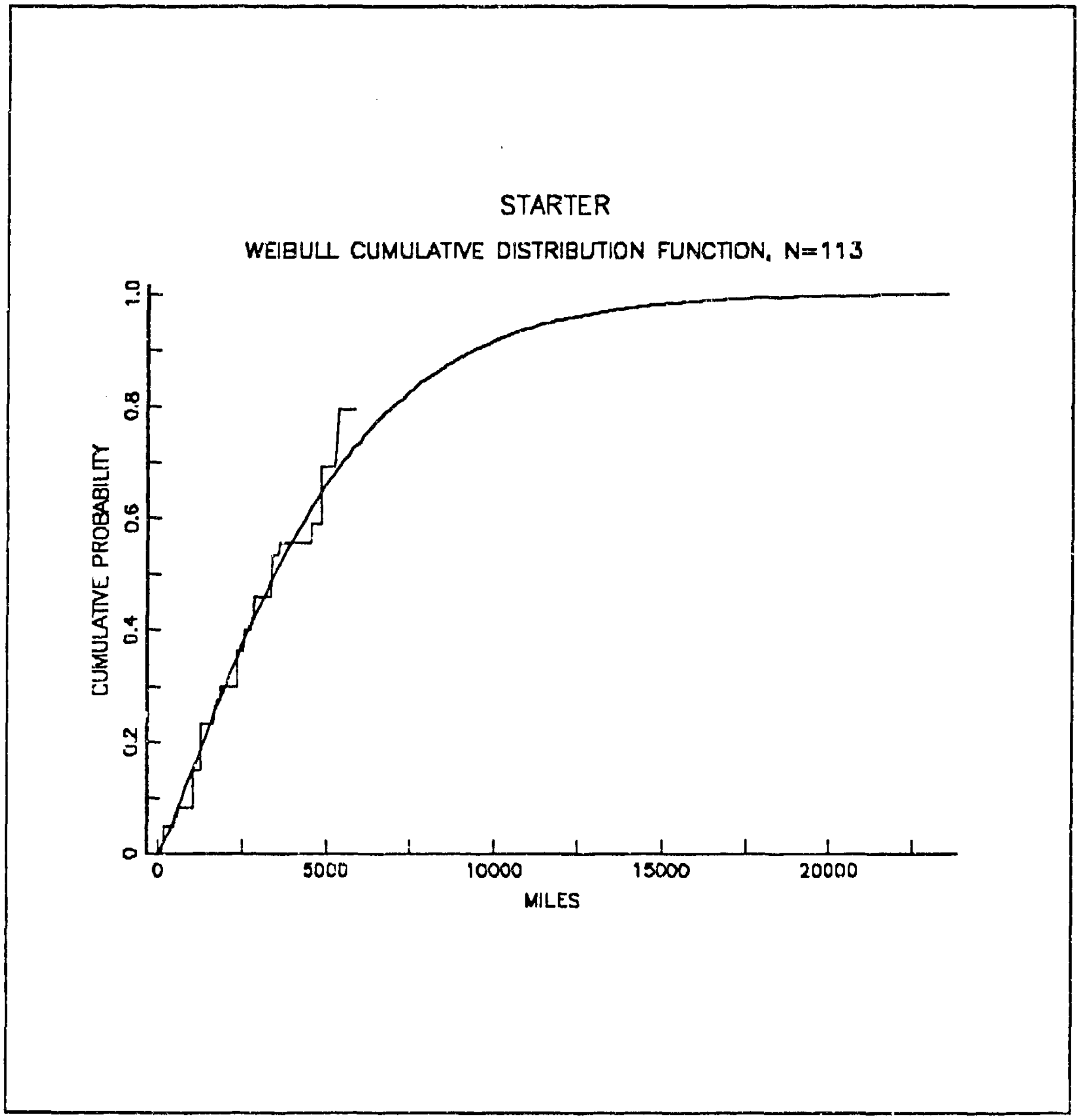

Figure 12. Starter Distribution Fit

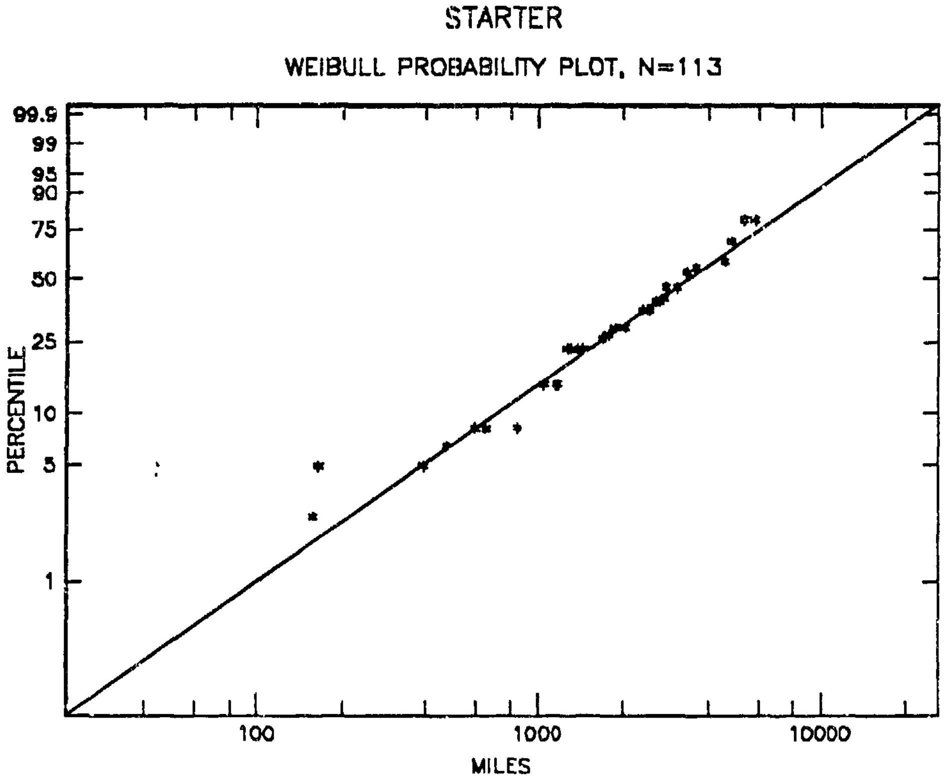

Figure 13. Starter Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA : STARTER
SELECTION : ALL
X AXIS LABEL: MILES
SAMPLE SIZE : 113
CENSORING : GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	°
C (SHAPE)	1.1999	0.91873	1.4811	0.020572	2.9477E1
° (SCALE)	4689.7	3580.5	5798.8	29.477	3.2013E5

	SAMPLE*	FITTED
MEAN :	1974.4	4411.4
STD DEV :	1280.8	3692.2
SKEWNESS:	0.54258	1.5213
KURTOSIS:	2.6874	6.2366

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	471	394.56
10:	10[illegible].5	718.86
25:	1660	1660.4
50:	3352.5	3455.3
75:	5301	6156.9
90:		9397.5
95:		11702

* BASED ON TURNBULL'S ESTIMATE

B. TRANSMISSION

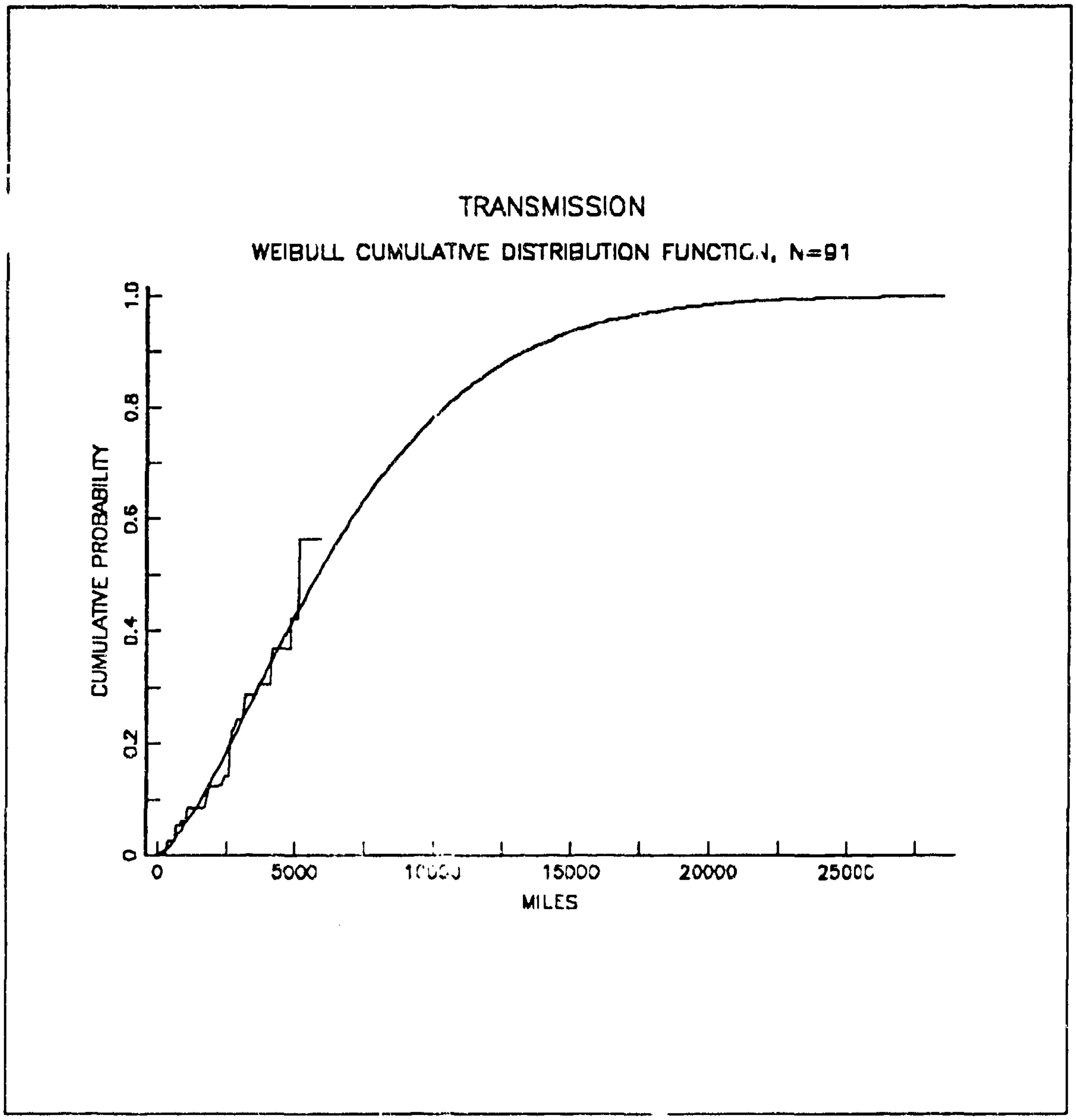

Figure 14. Transmission Distribution Fit

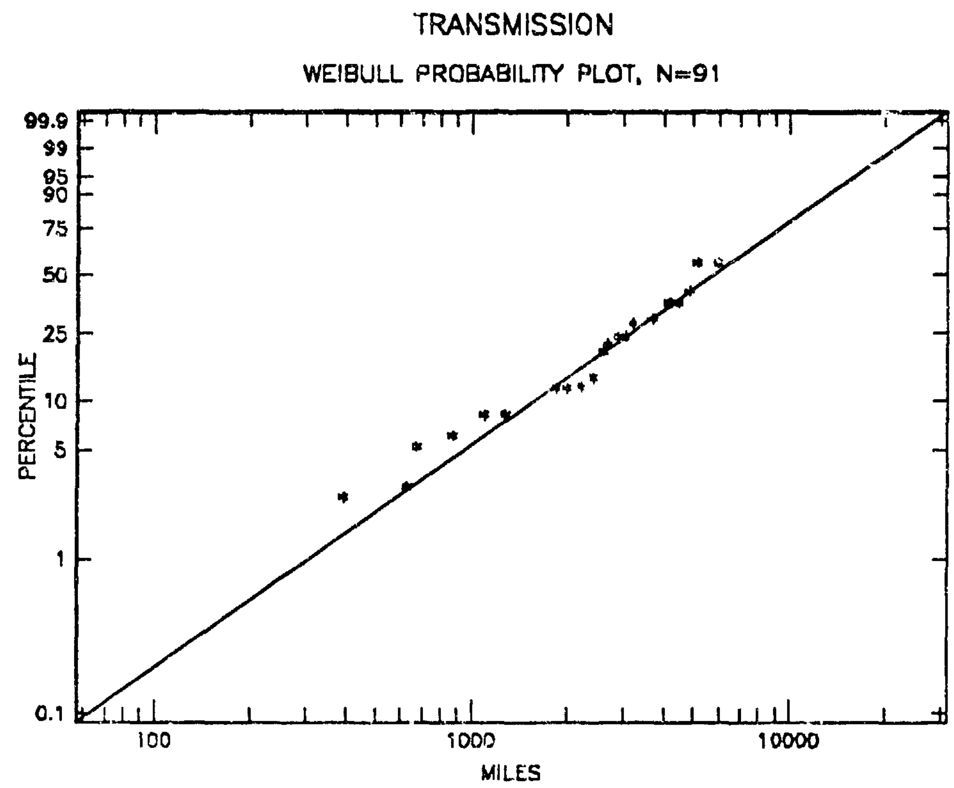

Figure 15. Transmissionr Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA : TRANSMISSION
SELECTION : ALL
X AXIS LABEL: MILES
SAMPLE SIZE : 91
CENSORING : GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	°
C (SHAPE)	1.4455	0.9569	1.934	0.062105	2.0929E2
° (SCALE)	7479.5	4952.5	10007	209.29	1.6616E6

	SAMPLE*	FITTED
MEAN :	2441.2	6784.8
STD DEV :	1325.1	4767
SKEWNESS:	0.040961	1.1387
KURTOSIS:	2.2564	4.6203

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	665	958.21
10:	1777.5	1576.7
25:	3153.5	3158.9
50:	5122	5804.3
75:		9375.9
90:		13319
95:		15978

* BASED ON TURNBULL'S ESTIMATE

C. GRIP

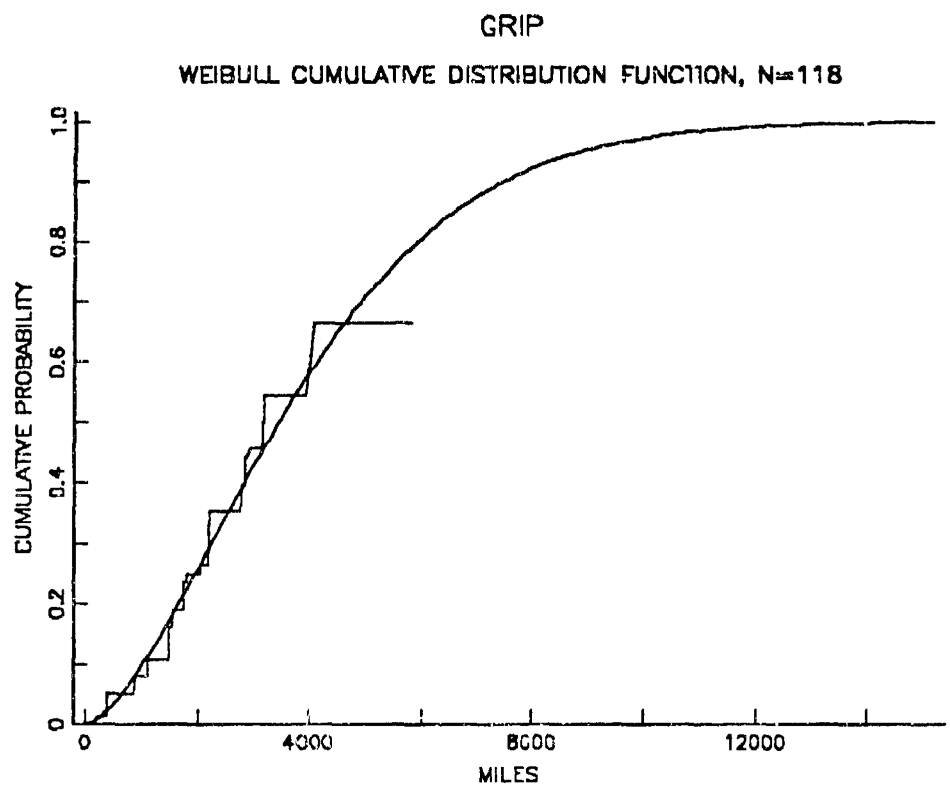

Figure 16. Grip Distribution Fit

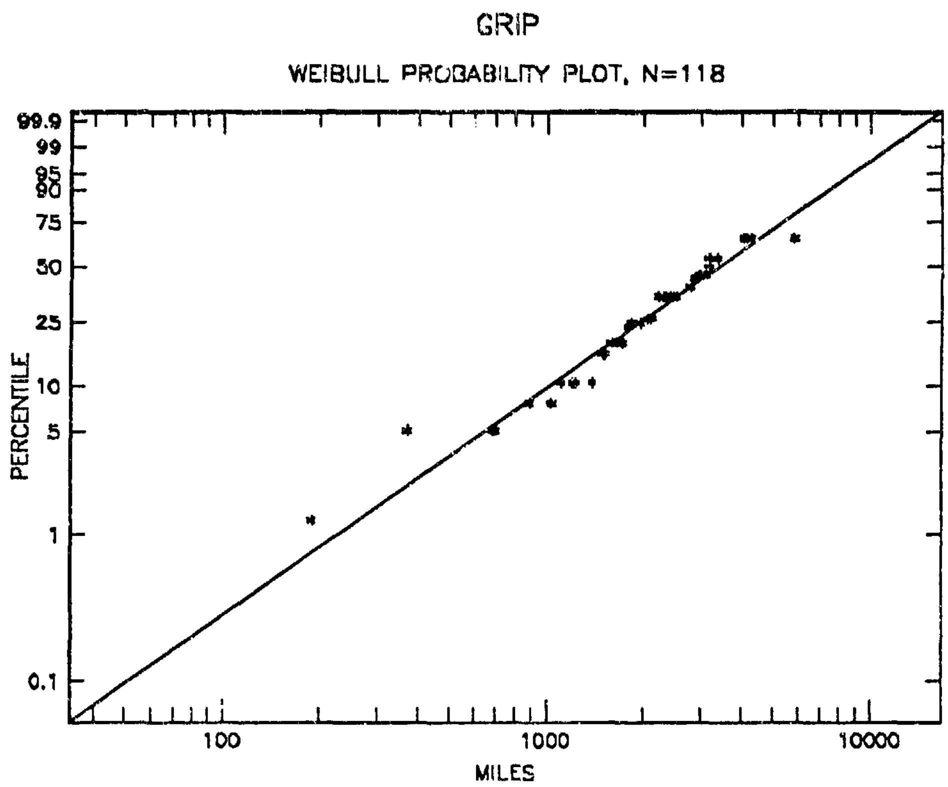

Figure 17. Grip Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA : GRIP
SELECTION : ALL
X AXIS LABEL: MILES
SAMPLE SIZE : 118
CENSORING : GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	°
C (SHAPE)	1.5539	1.1948	1.913	0.033552	3.0428E1
° (SCALE)	4369.9	3538.7	5201.1	30.428	1.7976E5

	SAMPLE*	FITTED
MEAN :	2060.9	3929.2
STD DEV :	1072.3	2582.6
SKEWNESS:	0.10384	1.0109
KURTOSIS:	2.2689	4.1929

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	365.5	646.17
10:	1108.5	1026.9
25:	2039	1960
50:	3160	3451.7
75:		5392.1
90:		7474.3
95:		8853.6

* BASED ON TURNBULL'S ESTIMATE

D. NOZZLE

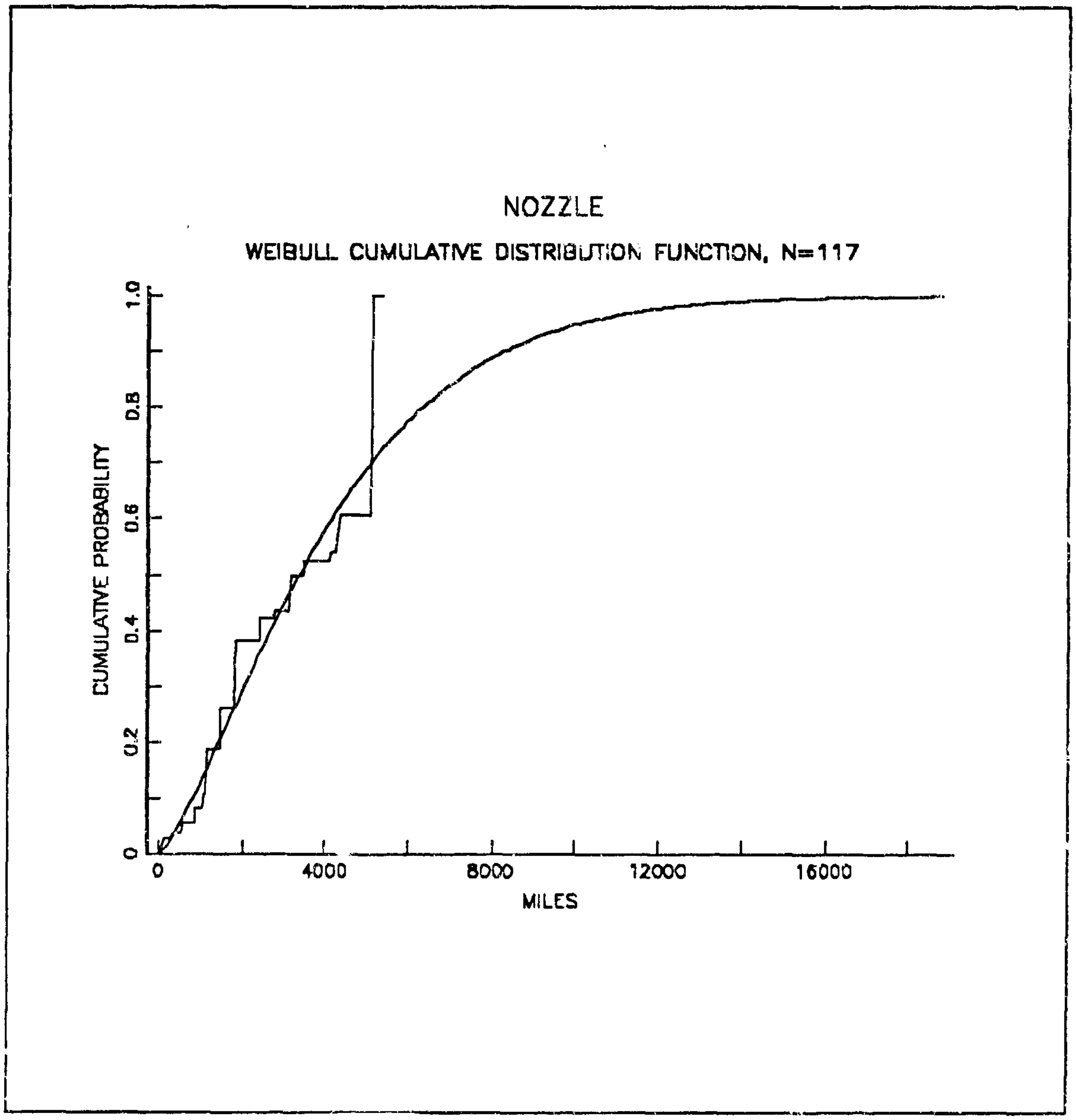

Figure 18. Nozzle Distribution Fit

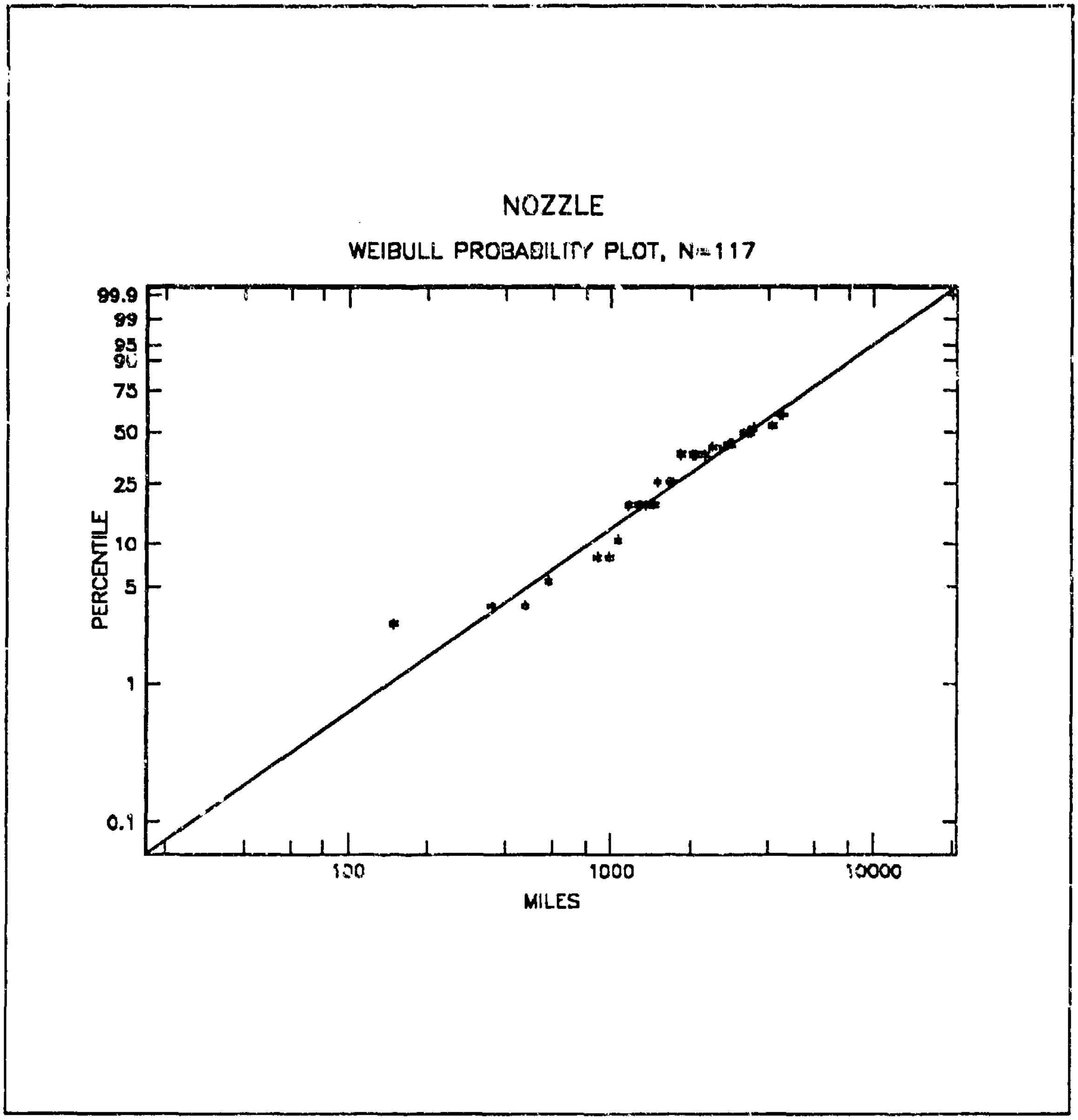

Figure 19. Nozzle Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA	:	NOZZLE
SELECTION	:	ALL
X AXIS LABEL	:	MILES
SAMPLE SIZE	:	117
CENSORING	:	GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES	:	1
EST. METHOD	:	MAXIMUM LIKELIHOOD
CONF METHOD	:	ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	°
C (SHAPE)	1.3384	1.0287	1.6482	0.024967	2.9137E1
° (SCALE)	4438.7	3490.1	5387.2	29.137	2.3412E5

	SAMPLE*	FITTED
MEAN :	1925.3	4076.5
STD DEV :	1223.4	3077
SKEWNESS:	0.91959	1.2864
KURTOSIS:	3.4006	5.1839

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	571	482.47
10:	1057	826.11
25:	1489	1749.7
50:	3457	3375.4
75:	5124	5665.5
90:	5124	8277.2
95:	5124	10076

* BASED ON TURNBULL'S ESTIMATE

E. DISTBOX

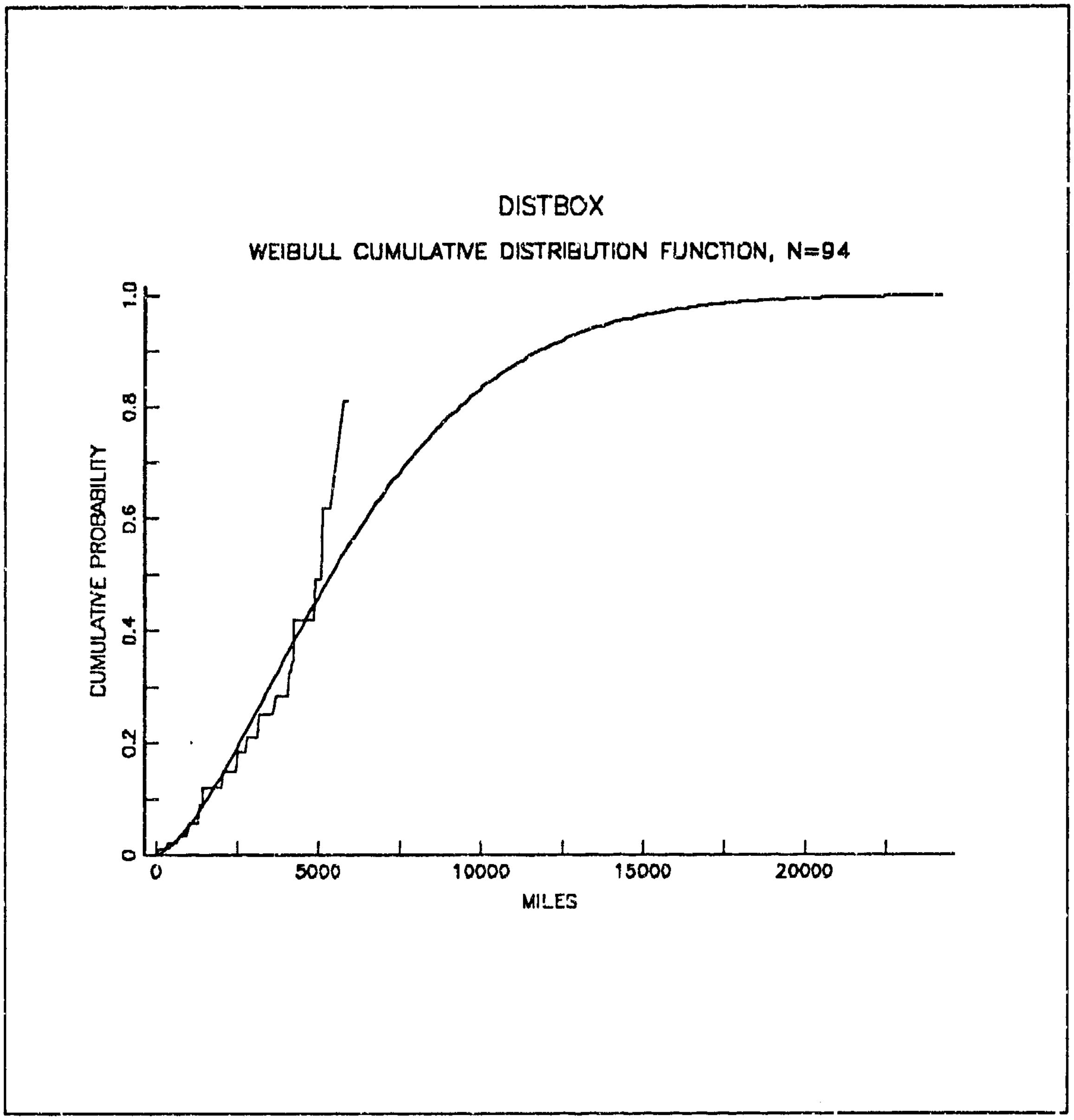

Figure 20. Distbox Distribution Fit

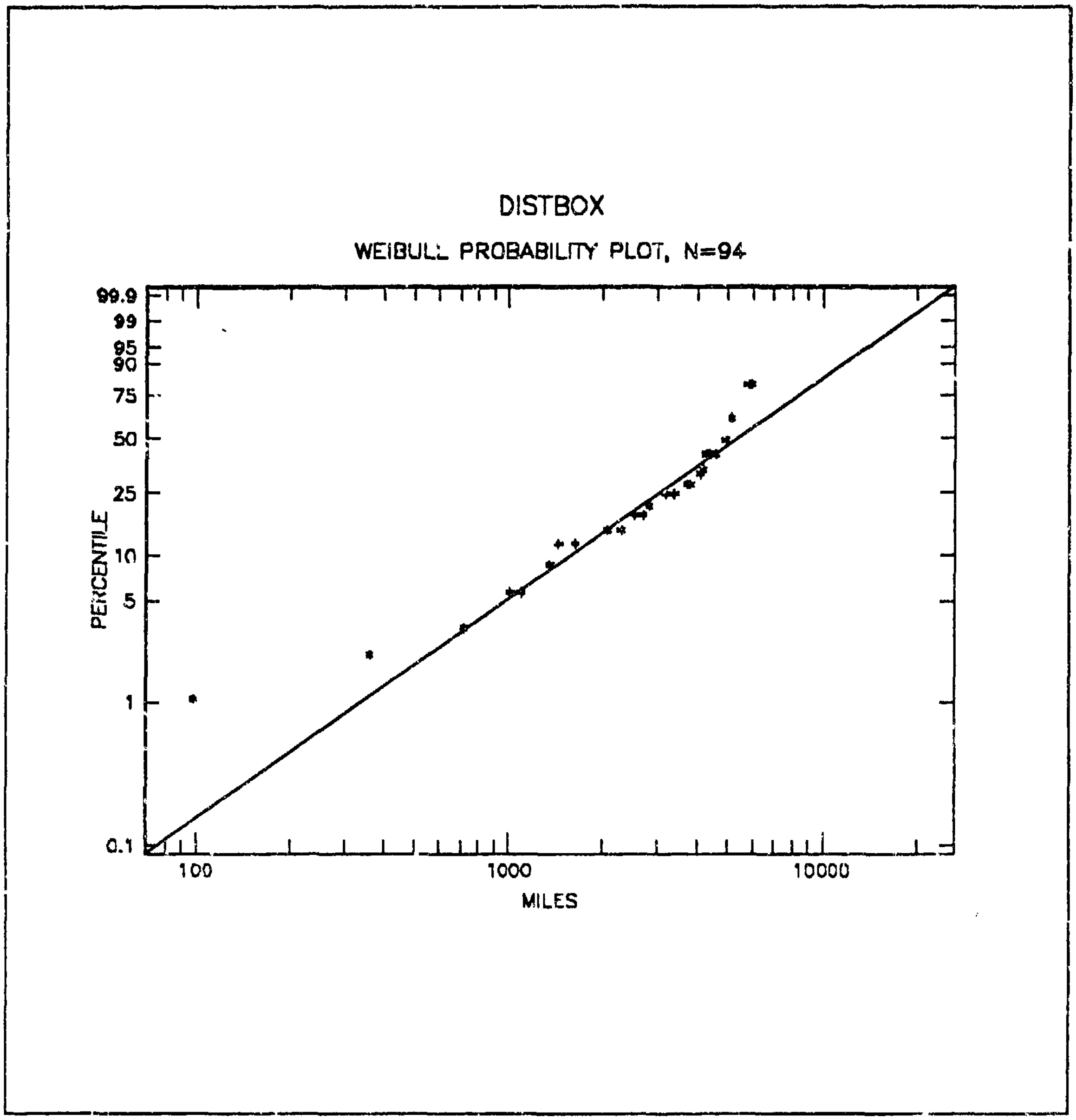

Figure 21. Distbox Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA : DISTBOX
SELECTION : ALL
X AXIS LABEL: MILES
SAMPLE SIZE : 94
CENSORING : GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	θ
C (SHAPE)	1.5315	1.0412	2.0217	0.062543	1.5897E2
θ (SCALE)	6858.6	4828.2	8889.1	158.97	1.0727E6

	SAMPLE*	FITTED
MEAN :	2705.2	6176.7
STD DEV :	1535.9	4114.4
SKEWNESS:	0.0087015	1.0358
KURTOSIS:	1.904	4.2719

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	975.5	986.16
10:	1431.5	1577.9
25:	3633.5	3040.4
50:	5111.5	5398.9
75:	5599	8489.2
90:		11824
95:		14040

* BASED ON TURNBULL'S ESTIMATE

F. LINK

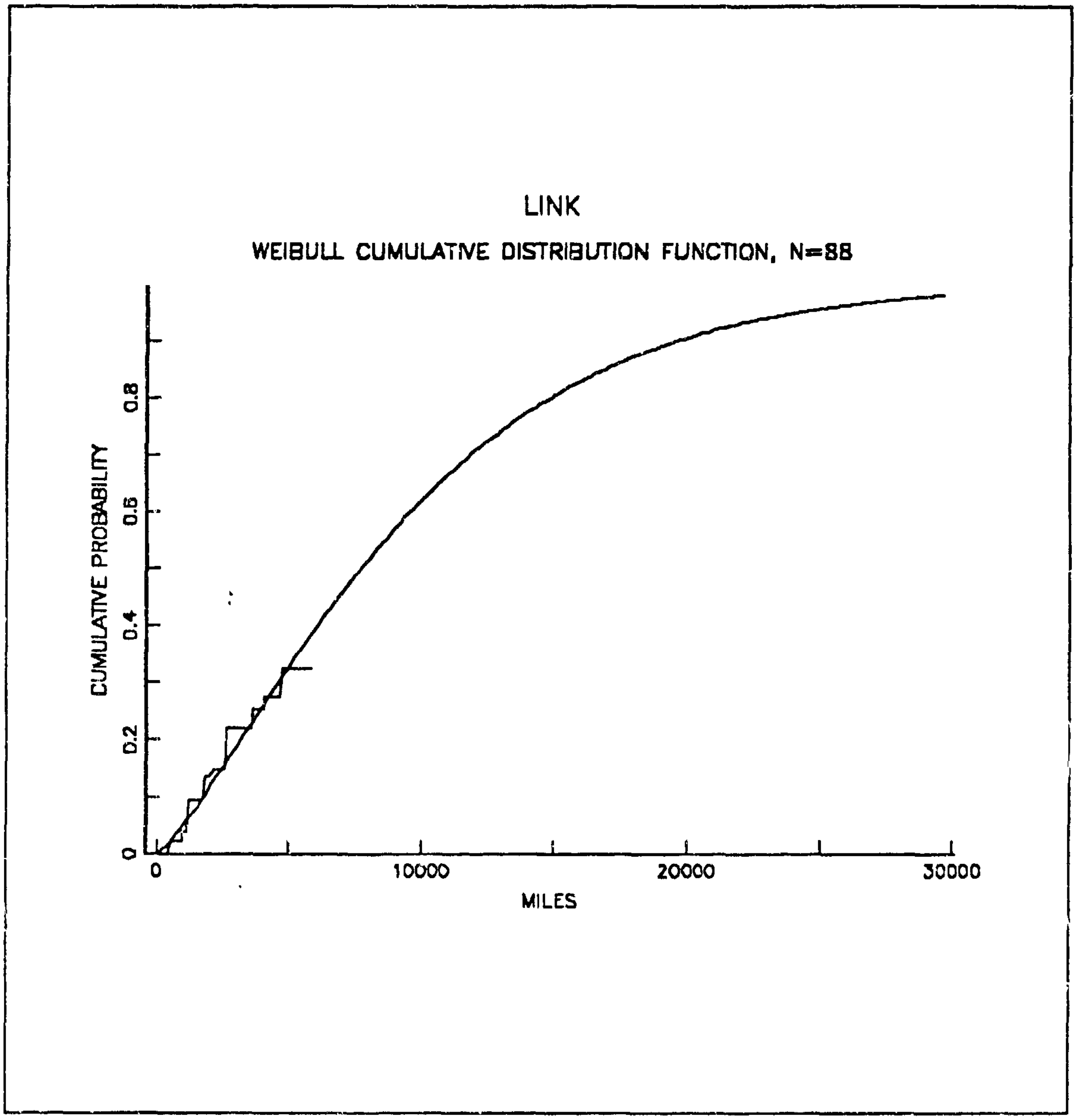

Figure 22. Link Distribution Fit

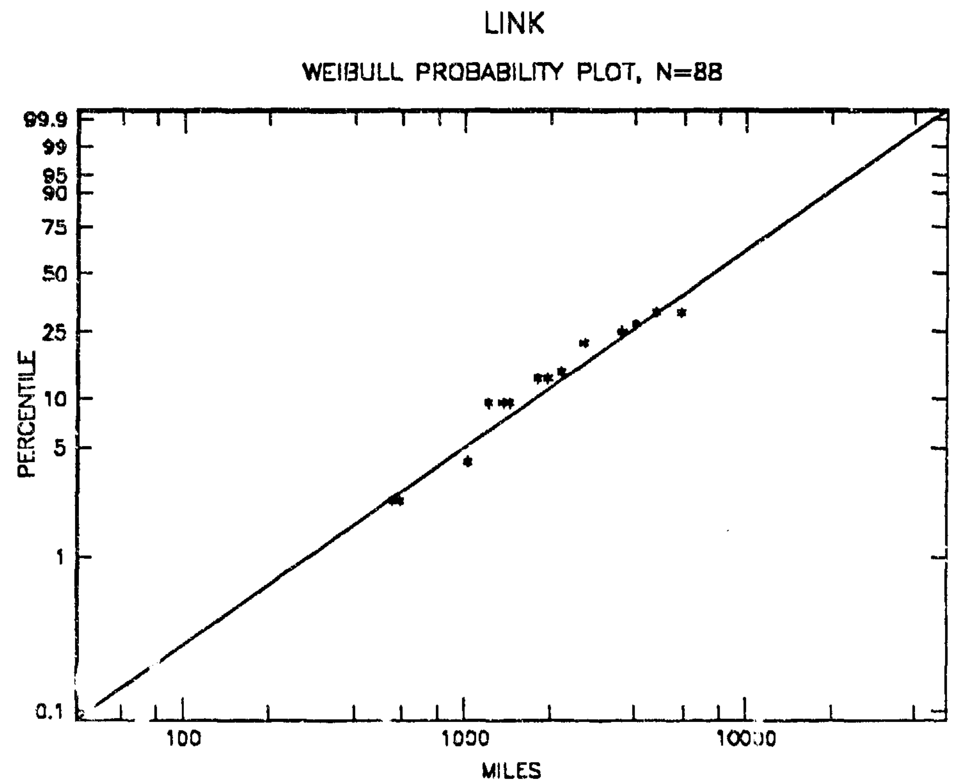

Figure 23. Link Percentile Plot

ANALYSIS OF WEIBULL DISTRIBUTION FIT

DATA : LINK
SELECTION : ALL
X AXIS LABEL: MILES
SAMPLE SIZE : 88
CENSORING : GROUPED DATA (CENSORING IS IMPLICIT)
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : ASYMPTOTIC NORMAL APPROXIMATION

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	C	θ
C (SHAPE)	1.2801	0.78478	1.7754	0.063837	5.0284E2
θ (SCALE)	10239	5049.7	15429	502.84	7.0077E6

	SAMPLE*	FITTED
MEAN :	2071.2	9486.9
STD DEV :	1137.5	7467
SKEWNESS:	0.57276	1.3783
KURTOSIS:	2.5741	5.5727

* BASED ON MIDPOINTS OF FINITE INTERVALS

GOODNESS OF FIT
NOT AVAILABLE

PERCENTILES	SAMPLE*	FITTED
5:	1196.5	1006
10:	1753	1765.2
25:	3592.5	3868.8
50:		7689.9
75:		13215
90:		19644
95:		24127

* BASED ON TURNBULL'S ESTIMATE

APPENDIX D. DELAY FITS

A. STARTER

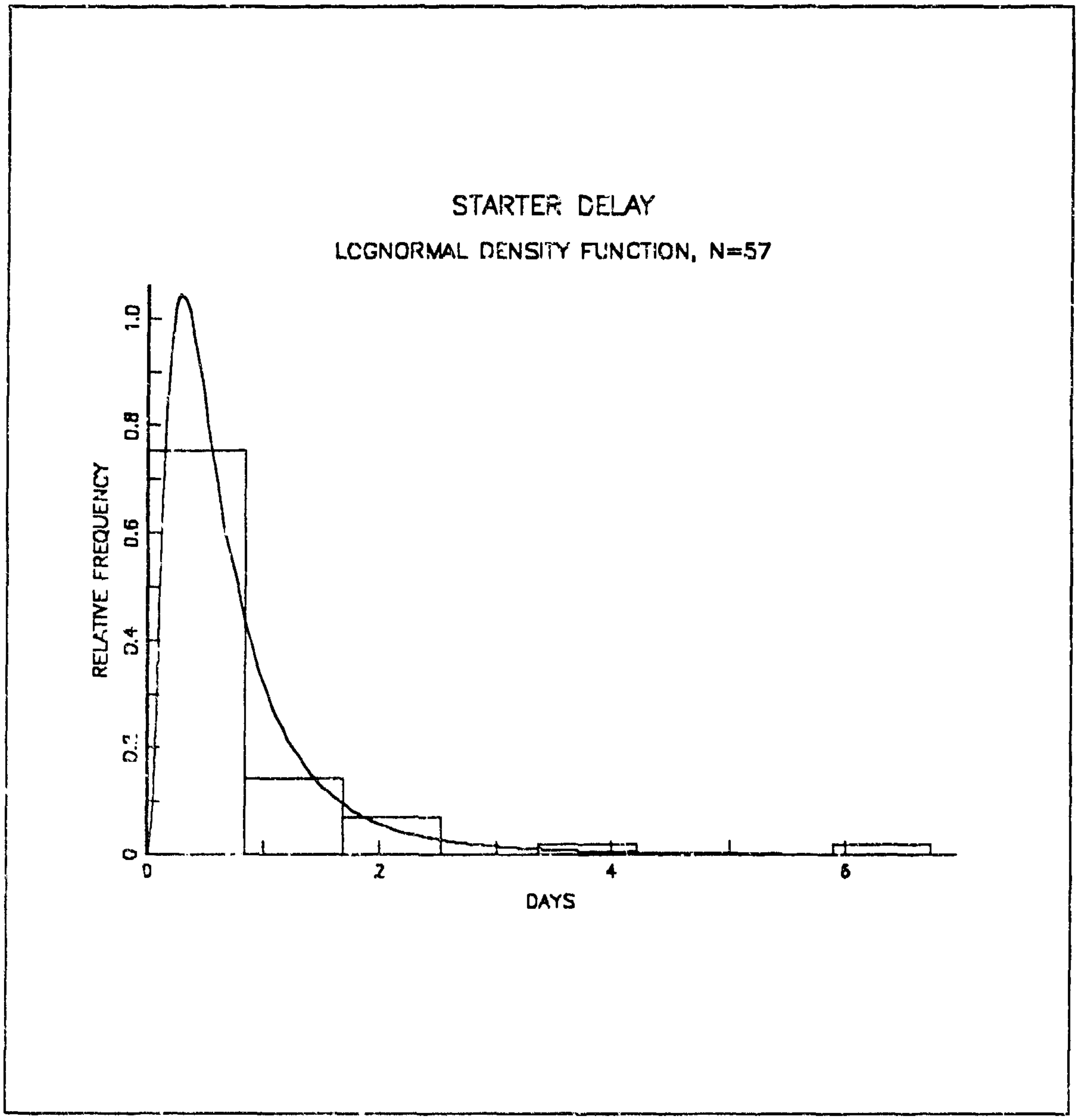

Figure 24. Starter Delay Histogram

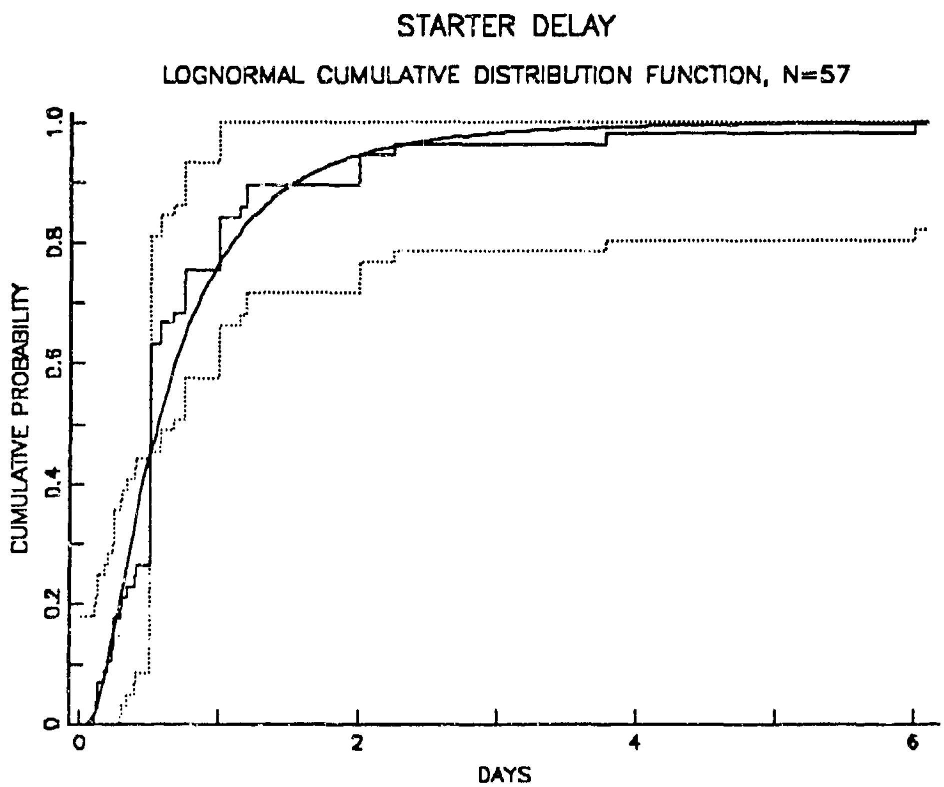

Figure 25. Starter Delay Distribution Fit

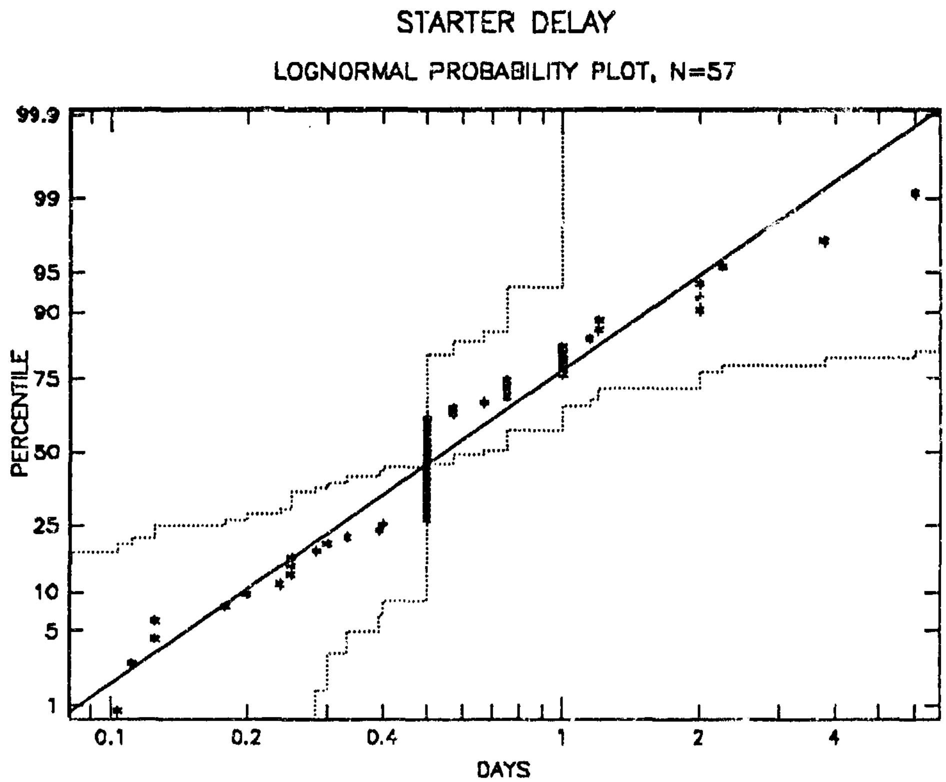

Figure 26. Starter Delay Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA	:	STARTER
SELECTION	:	ALL
X AXIS LABEL	:	DAYS
SAMPLE SIZE	:	57
CENSORING	:	NONE
FREQUENCIES	:	1
EST. METHOD	:	MAXIMUM LIKELIHOOD
CONF METHOD	:	EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.59102	0.80521	0.37683	0.011212	0
SIGMA	0.79943	0.6809	0.98954	0	0.0056061

	SAMPLE	FITTED
MEAN :	0.79685	0.76225
STD DEV :	0.94387	0.72103
SKEWNESS:	3.6941	3.6841
KURTOSIS:	18.884	34.264

PERCENTILES	SAMPLE	FITTED
5:	0.125	0.14864
10:	0.2	0.19876
25:	0.4	0.32304
50:	0.5	0.55376
75:	0.75	0.94928
90:	2	1.5429
95:	2.25	2.0631

GOODNESS OF FIT

KOLM-SMIRN	:	0.18602
SIGNIF	:	0.038716
CRAMER-V M	:	0.34074
SIGNIF	:	< .15
ANDER-DARL	:	1.5772
SIGNIF	:	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

B. TRANSMISSION

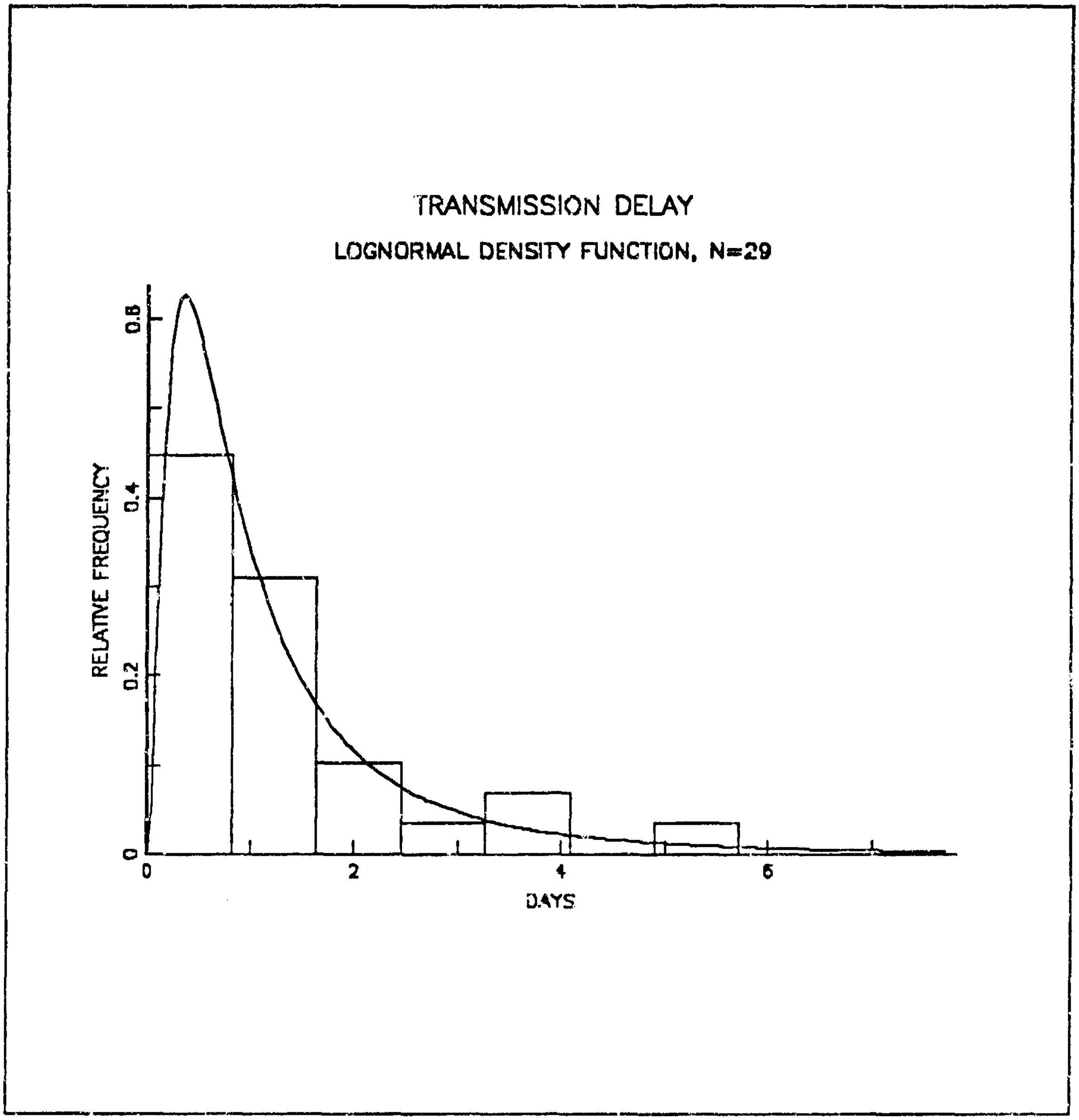

Figure 27. Transmission Delay Histogram

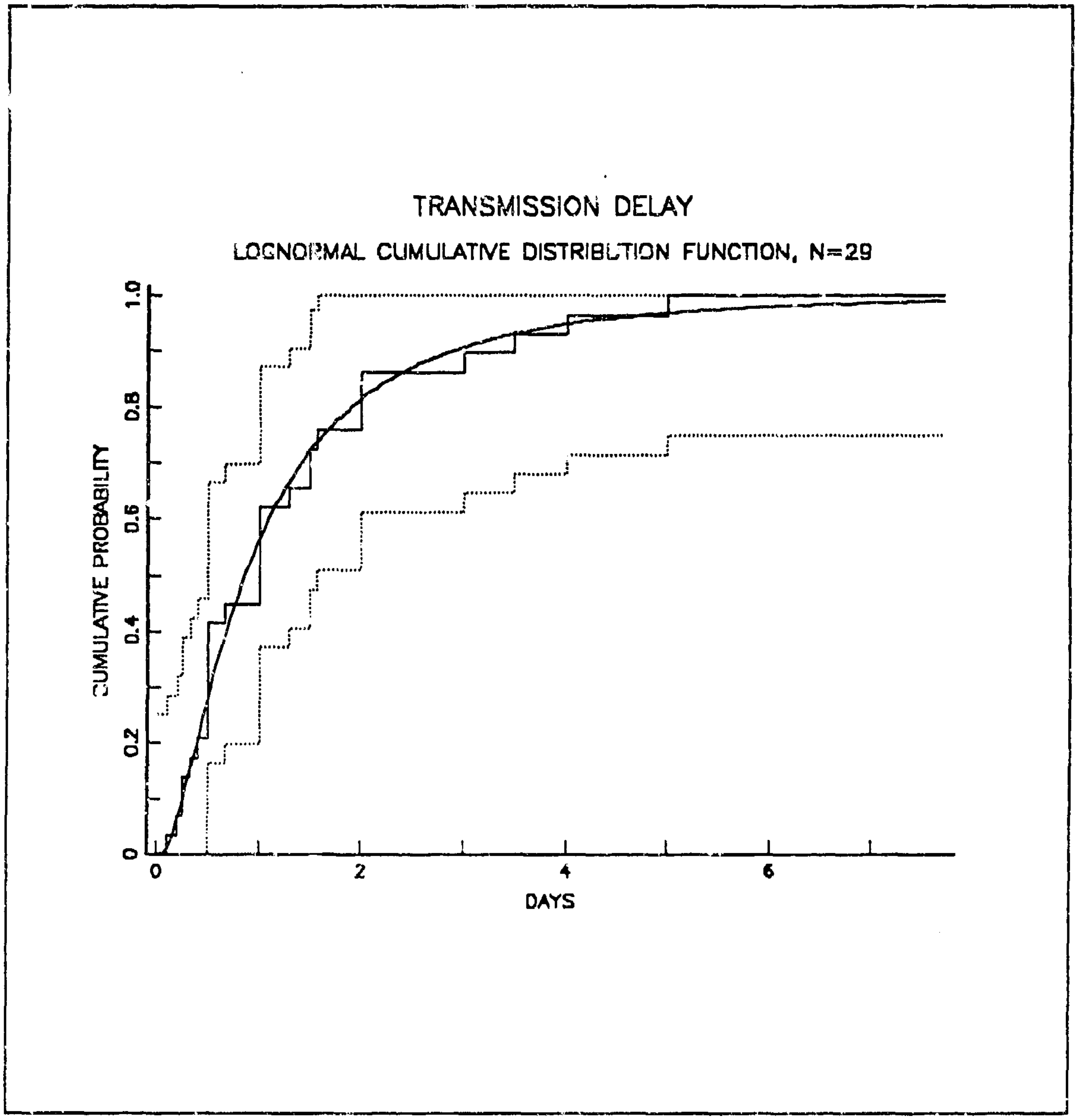

Figure 28. Transmission Delay Distribution Fit

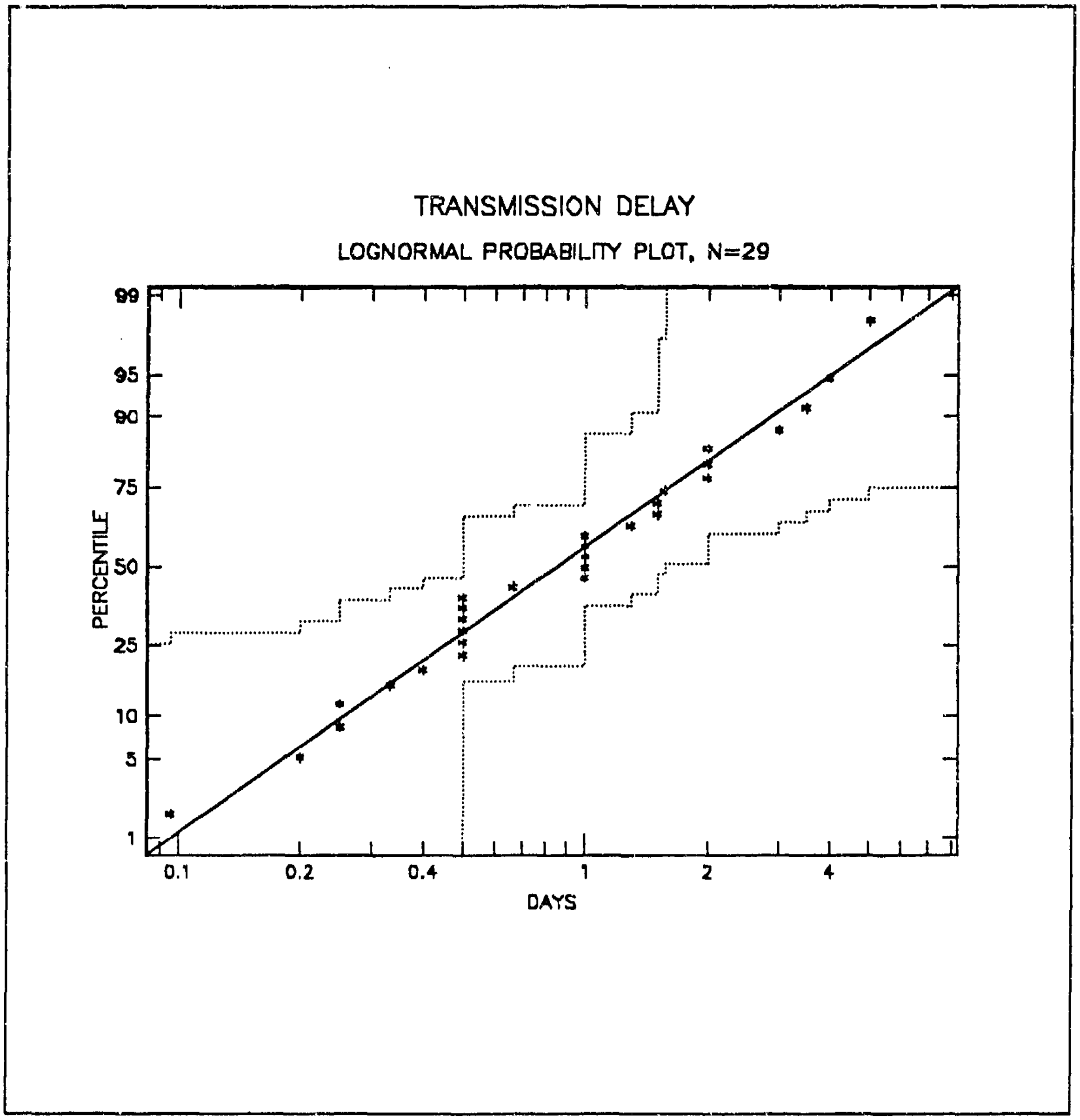

Figure 29. **Transmission Delay Percentile Plot**

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA	:	TRANSMISSION
SELECTION	:	ALL
X AXIS LABEL	:	DAYS
SAMPLE SIZE	:	29
CENSORING	:	NONE
FREQUENCIES	:	1
EST. METHOD	:	MAXIMUM LIKELIHOOD
CONF METHOD	:	EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.15064	0.51526	0.21398	0.030588	0
SIGMA	0.94184	0.76064	1.2964	0	0.015294

	SAMPLE	FITTED
MEAN :	1.295	1.3403
STD DEV :	1.2194	1.6016
SKEWNESS:	1.5456	5.2913
KURTOSIS:	4.7651	78.062

PERCENTILES	SAMPLE	FITTED
5:	0.2	0.18265
10:	0.25	0.25722
25:	0.5	0.45584
50:	1	0.86016
75:	1.5652	1.6231
90:	3.5	2.8764
95:	4	4.0506

GOODNESS OF FIT

CHI-SQUARE	:	0.23296
DEG FREED	:	1
SIGNIF	:	0.62934
KOLM-SMIRN	:	0.13149
SIGNIF	:	0.69773
CRAMER-V M	:	0.054591
SIGNIF	:	> .15
ANDER-DARL	:	0.29512
SIGNIF	:	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)*2)*E
-INF.	0.81746	13	13.875	0.87491	0.05517
0.81746	1.6349	9	7.9432	1.0568	0.1406
1.6349	2.4524	3	3.3254	0.32541	0.031842
2.4524	+INF.	4	3.8565	0.14351	0.0053407
TOTAL		29	29		0.23296

C. GRIP

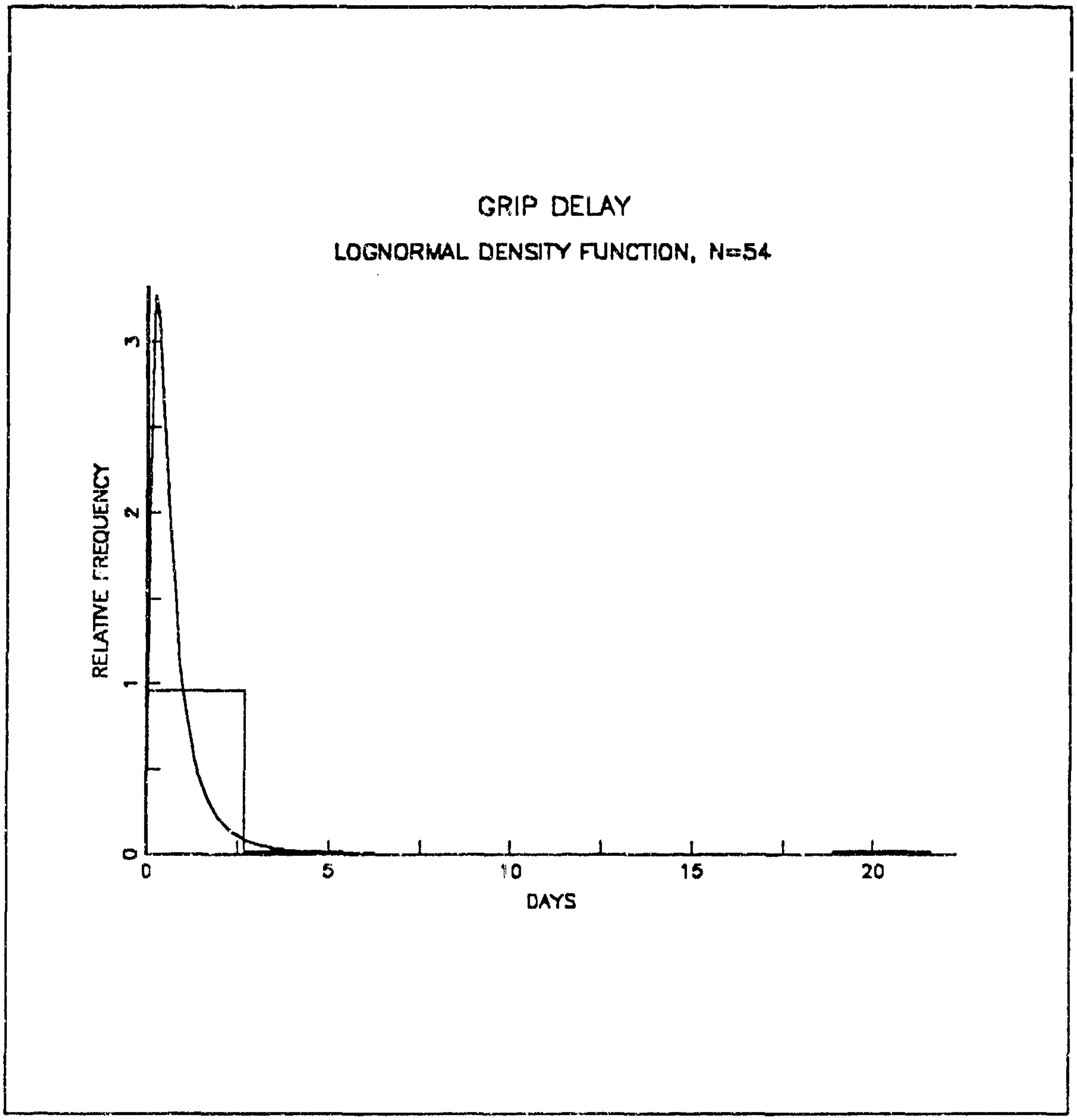

Figure 30. Grip Delay Histogram

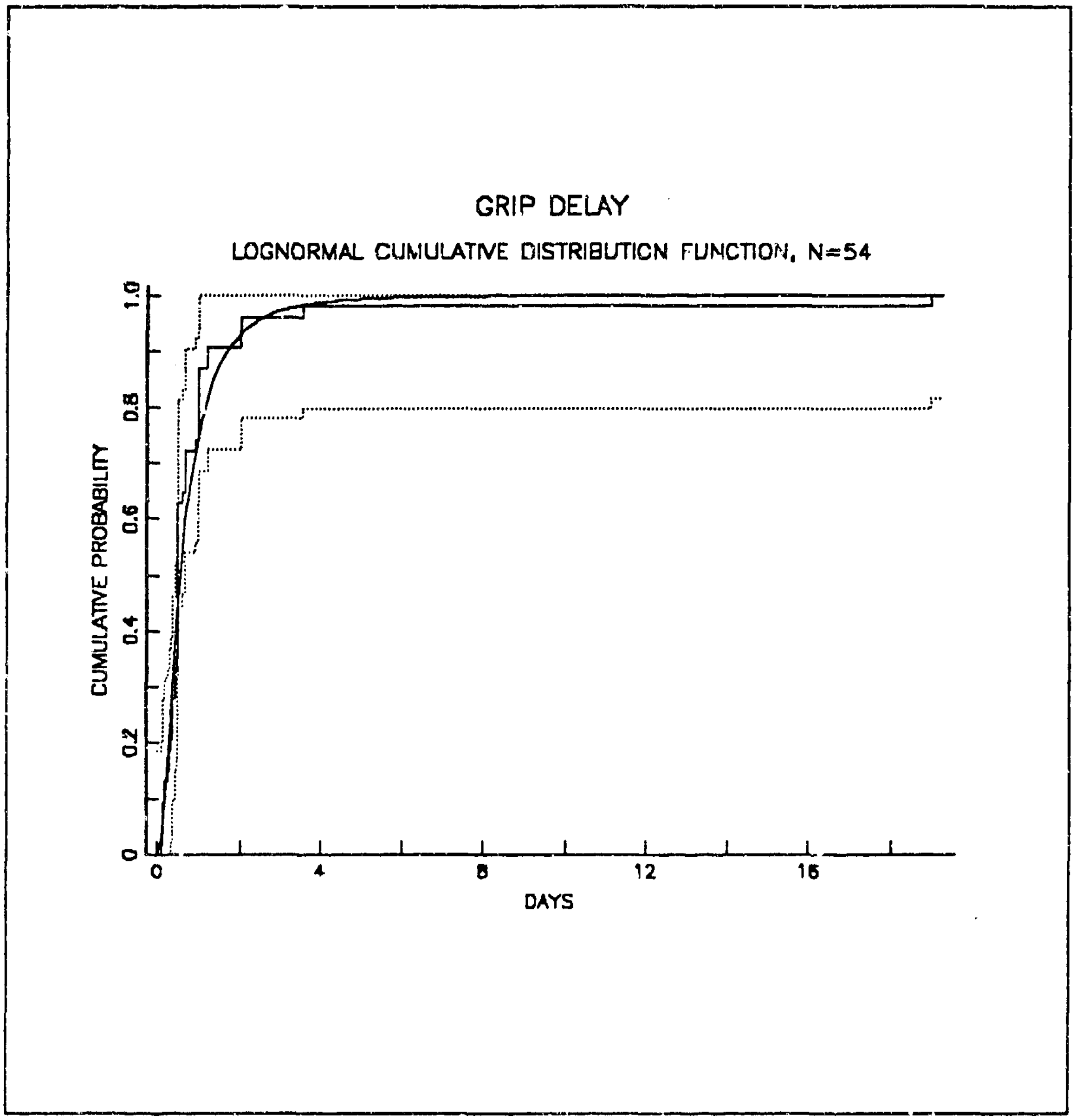

Figure 31. Grip Delay Distribution Fit

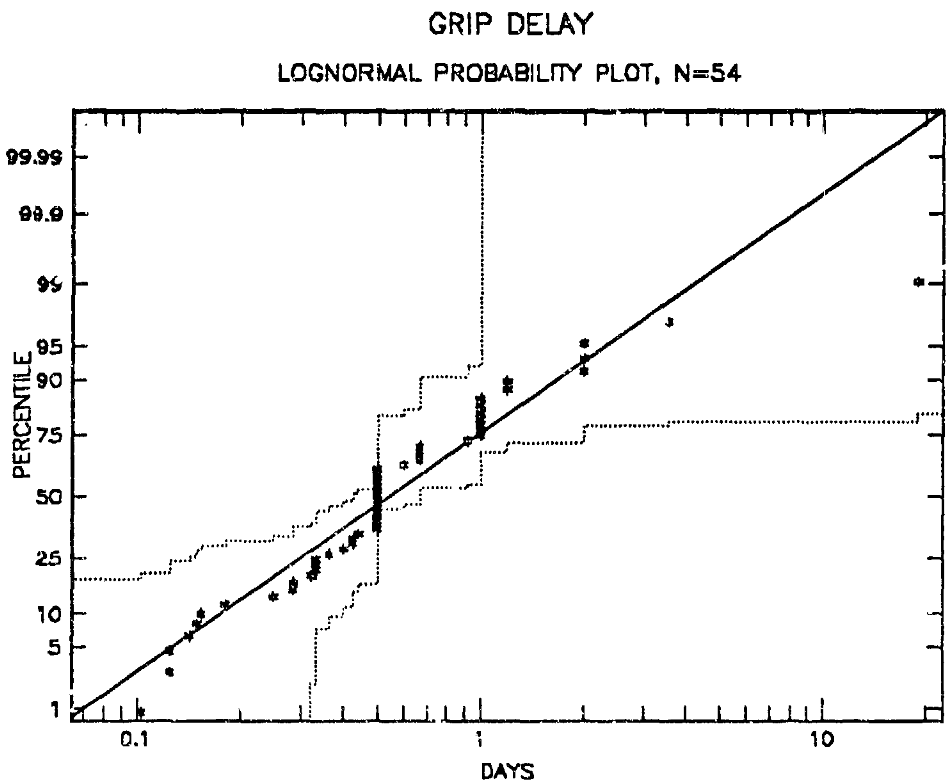

Figure 32. Grip Delay Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : GRIP
SELECTION : ALL
X AXIS LABEL: DAYS
SAMPLE SIZE : 54
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.60291	0.84539	0.36042	0.014336	0
SIGMA	0.87986	0.74655	1.0965	0	0.007168

	SAMPLE	FITTED
MEAN :	1.0154	0.80587
STD DEV :	2.5633	0.87121
SKEWNESS:	6.588	4.5068
KURTOSIS:	46.611	53.634

PERCENTILES	SAMPLE	FITTED
5:	0.125	0.12868
10:	0.15385	0.17717
25:	0.33333	0.30237
50:	0.5	0.54722
75:	1	0.99033
90:	1.2	1.6902
95:	2	2.3272

GOODNESS OF FIT

KOLM-SMIRN :	0.17048
SIGNIF :	0.086673
CRAMER-V M :	0.25423
SIGNIF :	> .15
ANDER-DARL :	1.3338
SIGNIF :	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

D. NOZZLE

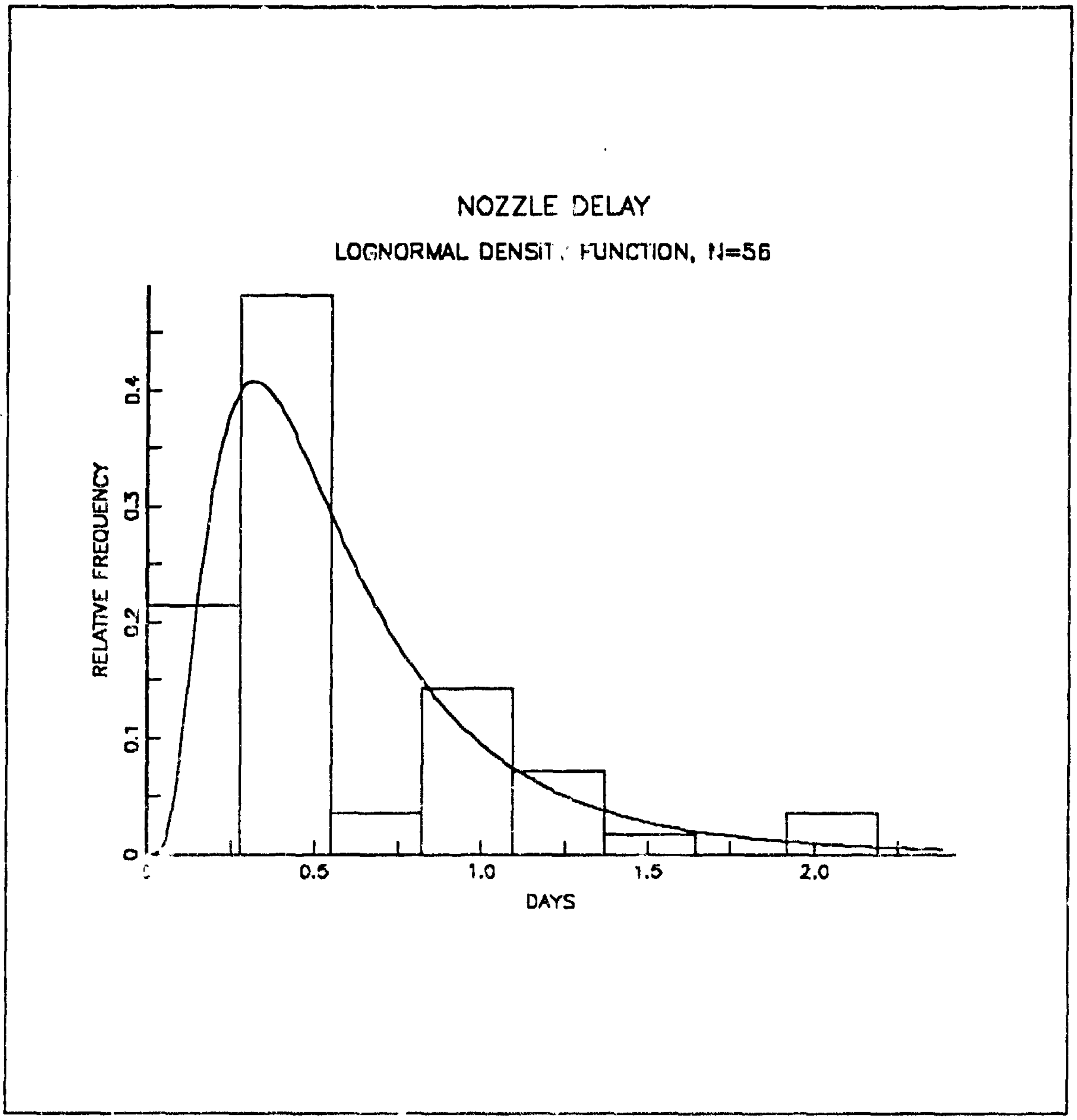

Figure 33. Nozzle Delay Histogram

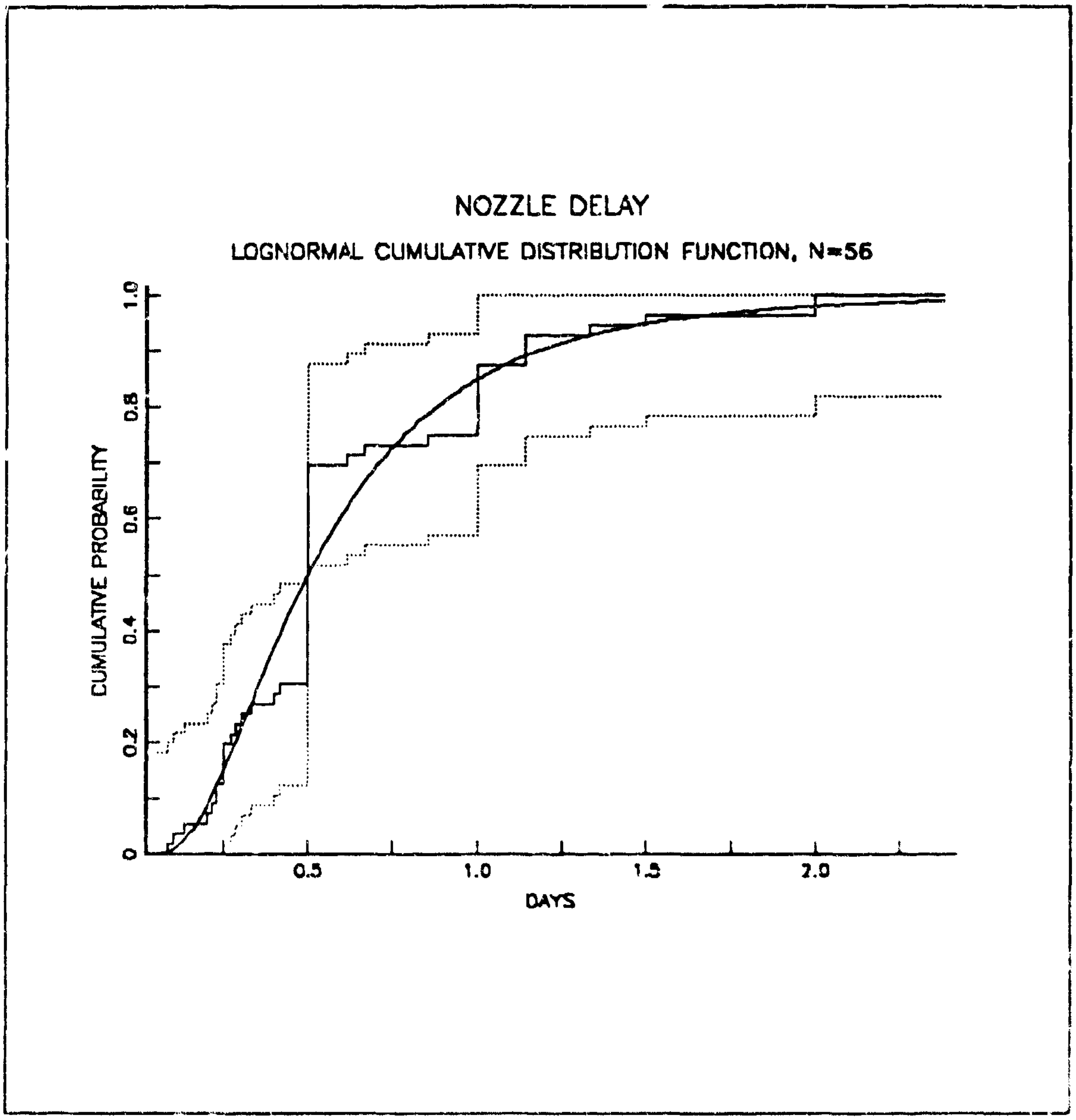

Figure 34. Nozzle Delay Distribution Fit

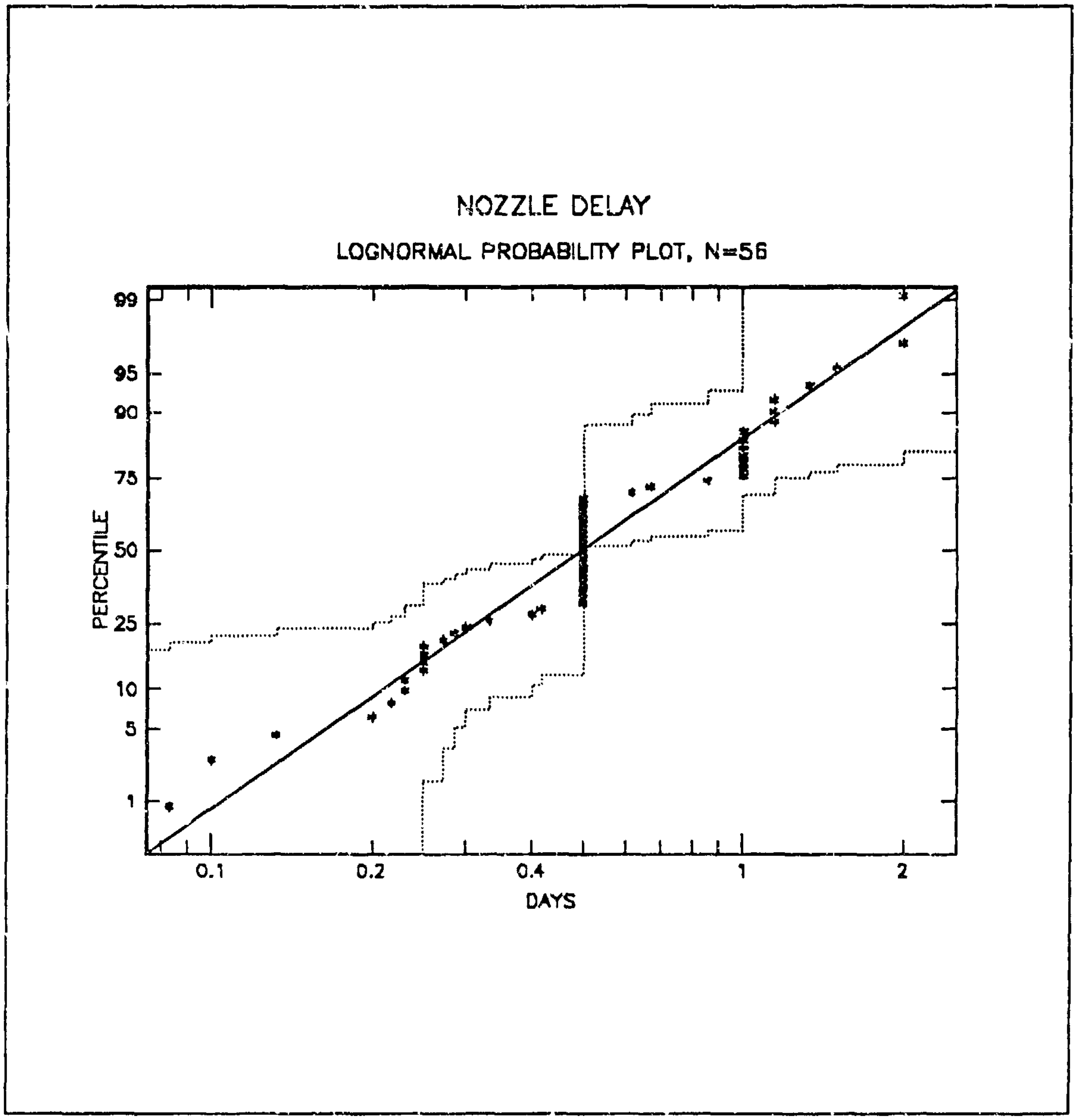

Figure 35. Nozzle Delay Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : NOZZLE
SELECTION : ALL
X AXIS LABEL: DAYS
SAMPLE SIZE : 56
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.69437	0.876	0.51275	0.0080534	0
SIGMA	0.67156	0.57128	0.83309	0	0.0040267

	SAMPLE	FITTED
MEAN :	0.61794	0.6257
STD DEV :	0.42191	0.47234
SKEWNESS:	1.4959	2.6949
KURTOSIS:	5.2464	18.205

PERCENTILES	SAMPLE	FITTED
5:	0.13208	0.16543
10:	0.23077	0.21116
25:	0.31667	0.31755
50:	0.5	0.49939
75:	0.92857	0.78536
90:	1.1429	1.181
95:	1.5	1.5075

GOODNESS OF FIT

CHI-SQUARE :	11.675
DEG FREED:	3
SIGNIF :	0.0085837
KOLM-SMIRN :	0.19716
SIGNIF :	0.025722
CRAMER-V M :	0.34086
SIGNIF :	< .15
ANDER-DARL :	1.552
SIGNIF :	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)*2)*E
-INF.	0.27381	12	10.384	1.6158	0.25143
0.27381	0.54762	27	20.673	6.3265	1.9361
0.54762	0.82143	2	12.1	10.1	8.4306
0.82143	1.0952	8	6.06	1.94	0.62102
1.0952	1.3691	4	3.0536	0.94643	0.29334
1.3691	+INF.	3	3.7287	0.72874	0.14242
TOTAL		56	56		11.675

E. DISTBOX

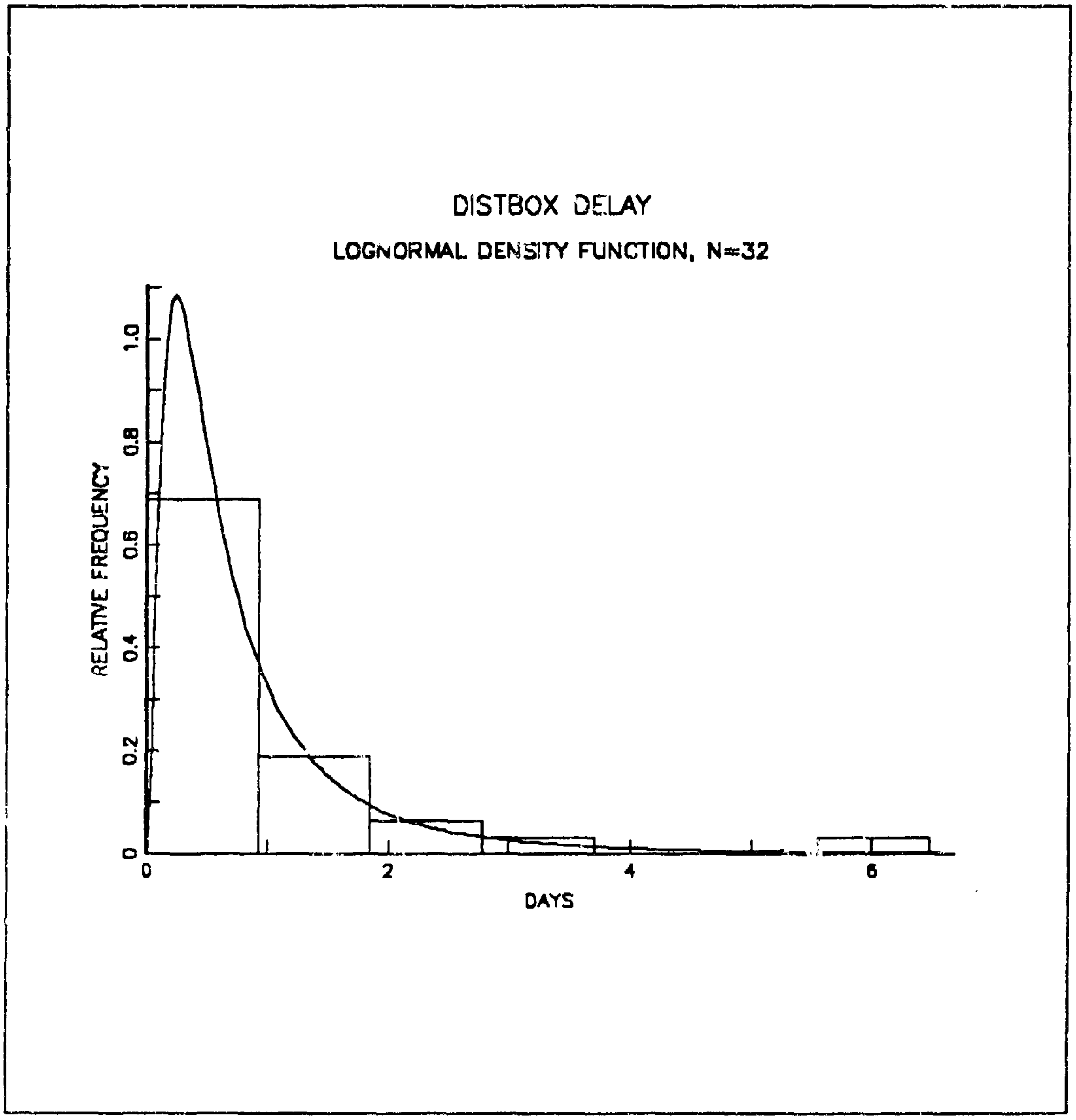

Figure 36. Distbox Delay Histogram

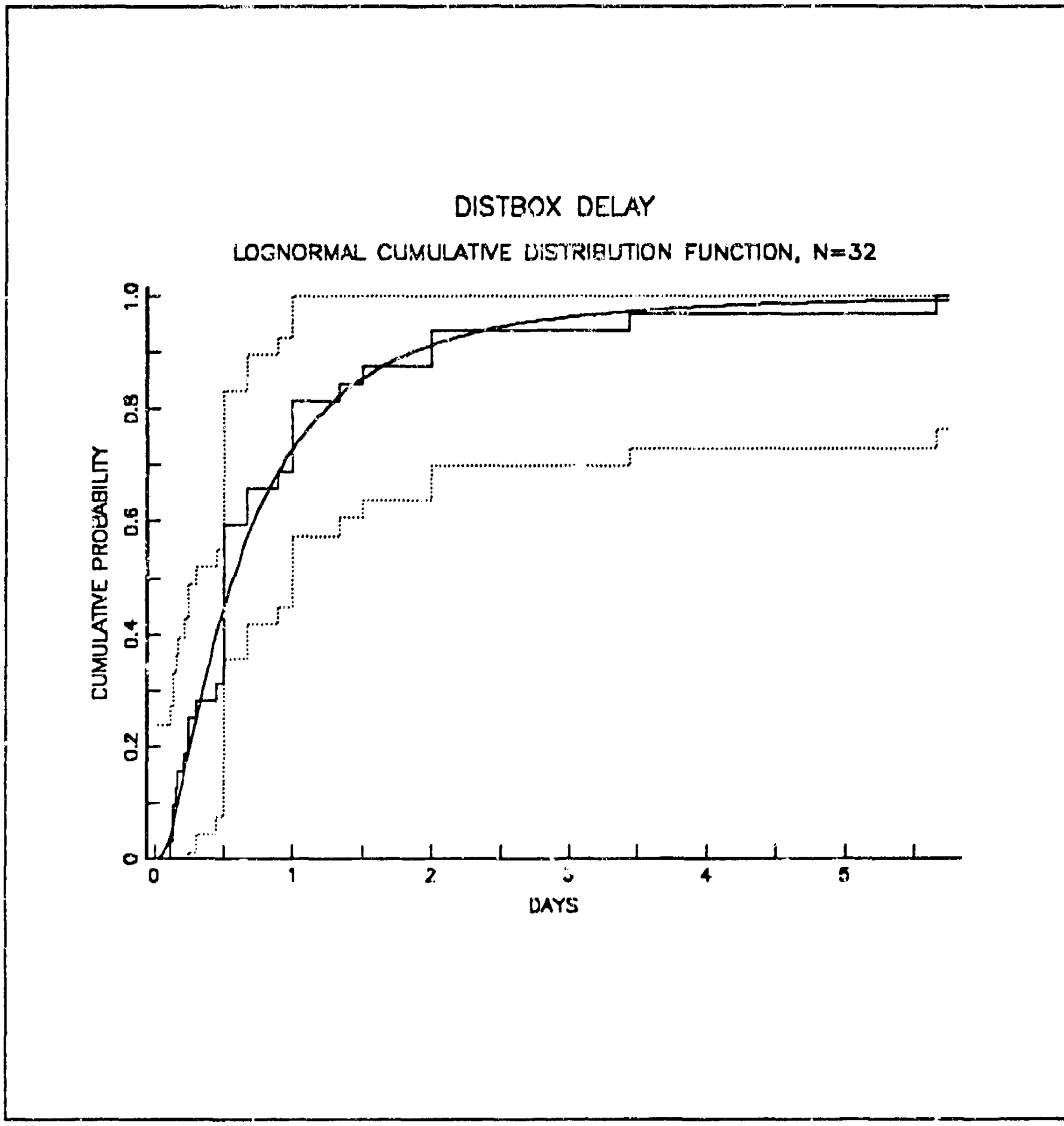

Figure 37. Distbox Delay Distribution Fit

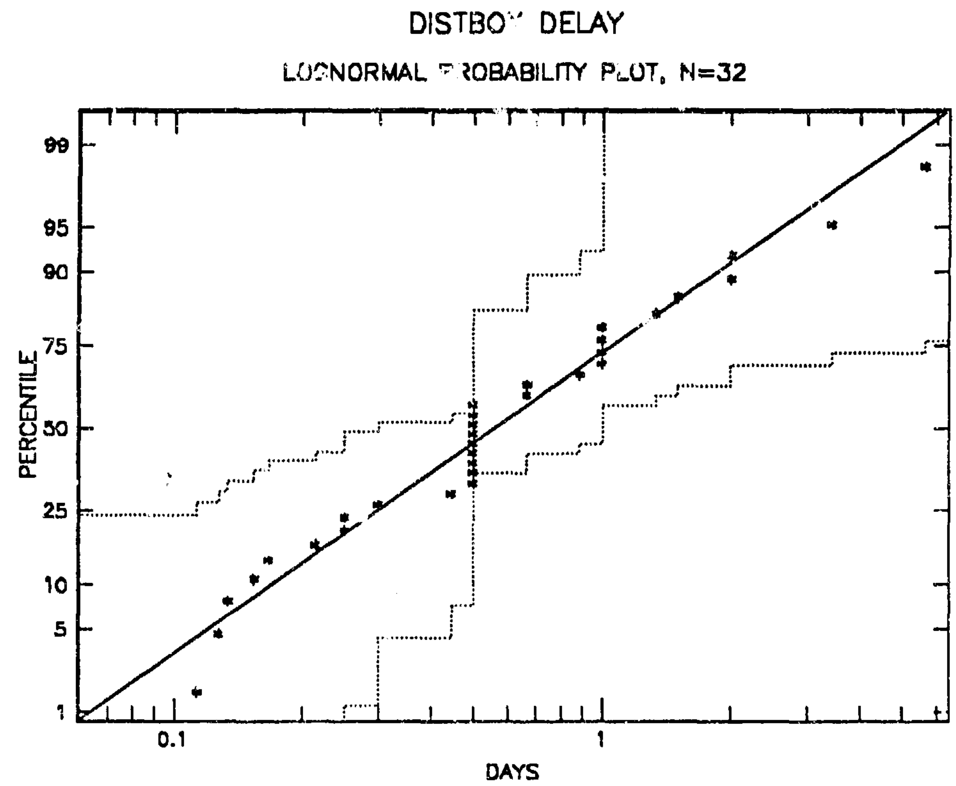

Figure 38. Distbox Delay Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA :	DISTBOX
SELECTION :	ALL
X AXIS LABEL:	DAYS
SAMPLE SIZE :	32
CENSORING :	NONE
FREQUENCIES :	1
EST. METHOD :	MAXIMUM LIKELIHOOD
CONF METHOD :	EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.57369	0.916	0.23139	0.027274	0
SIGMA	0.93421	0.76092	1.2624	0	0.013637

	SAMPLE	FITTED
MEAN :	0.90017	0.8717
STD DEV :	1.1137	1.029
SKEWNESS:	2.9283	5.1864
KURTOSIS:	12.181	74.429

PERCENTILES	SAMPLE	FITTED
5:	0.12766	0.12116
10:	0.154	0.17015
25:	0.275	0.30013
50:	0.5	0.56344
75:	1	1.0577
90:	2	1.8658
95:	3.4286	2.6203

GOODNESS OF FIT

KOLM-SMIRN :	0.14462
SIGNIF :	0.51498
CRAMER-V M :	0.092307
SIGNIF :	> .15
ANDER-DARL :	0.47943
SIGNIF :	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

F. LINK

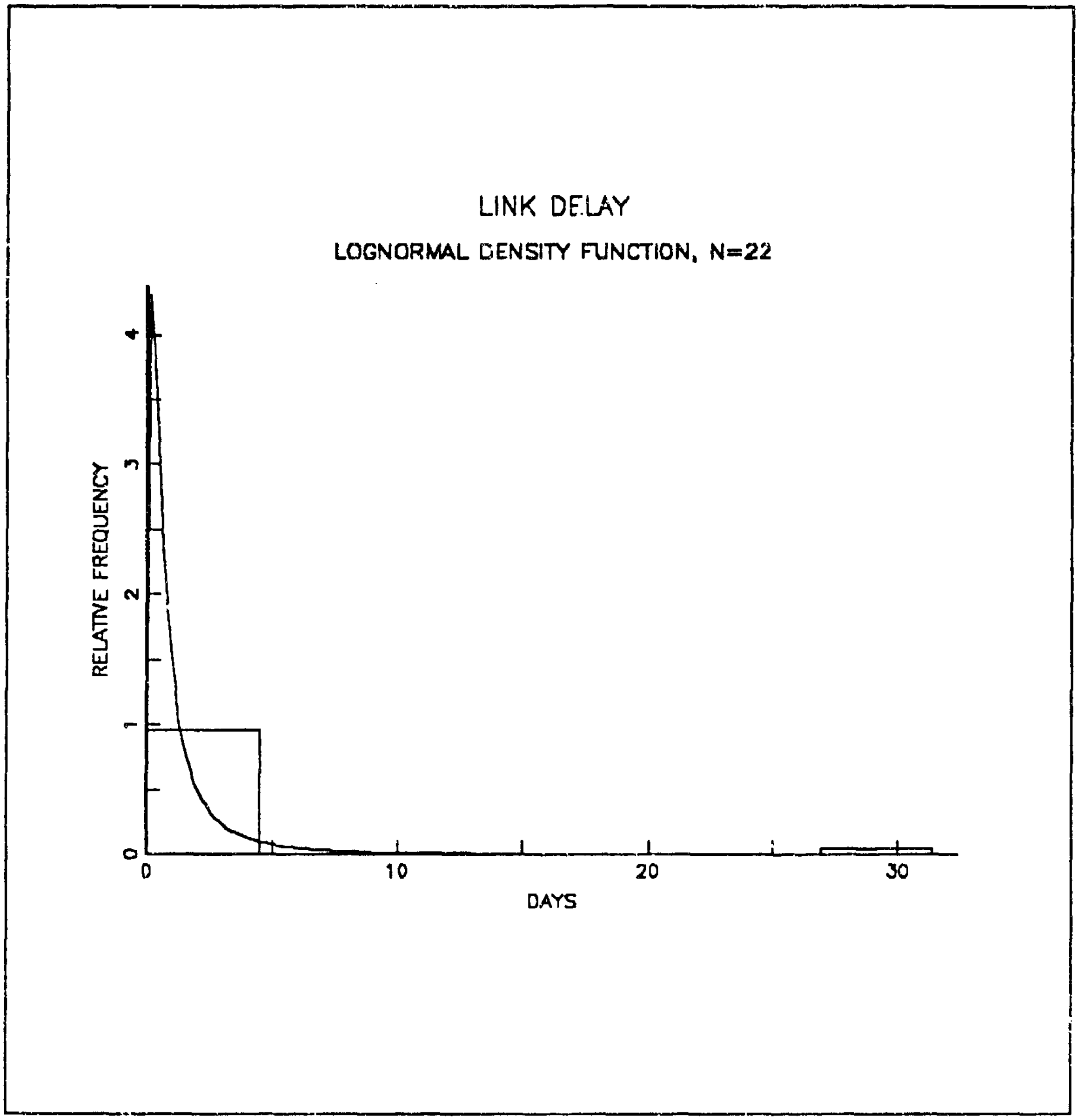

Figure 39. Link Delay Histogram

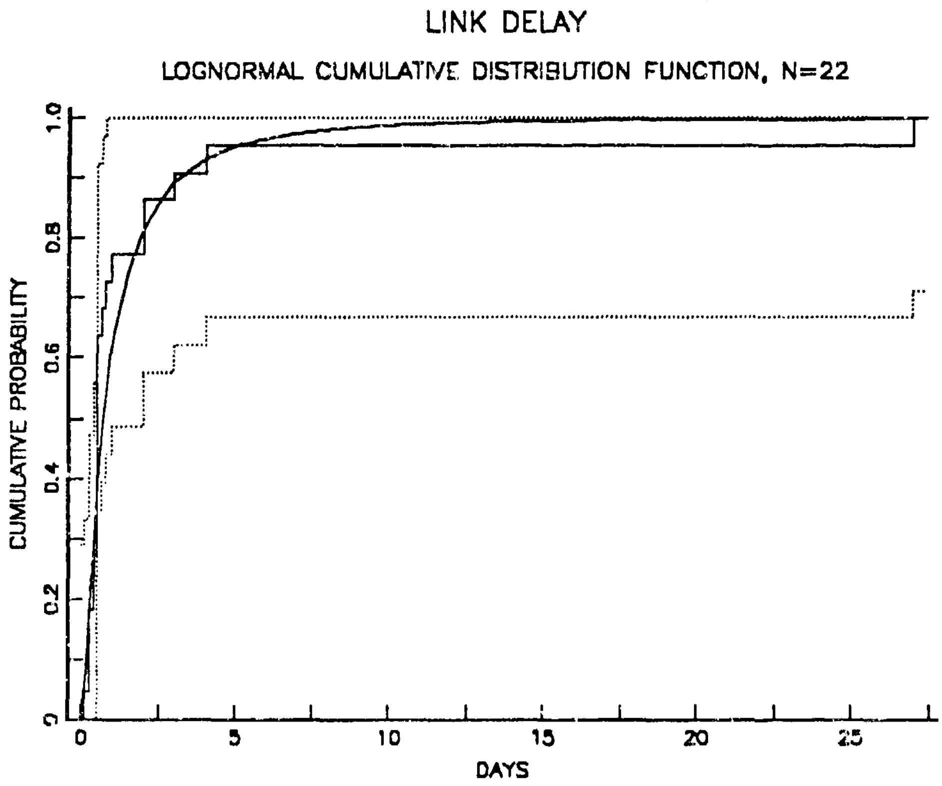

Figure 40. Link Delay Distribution Fit

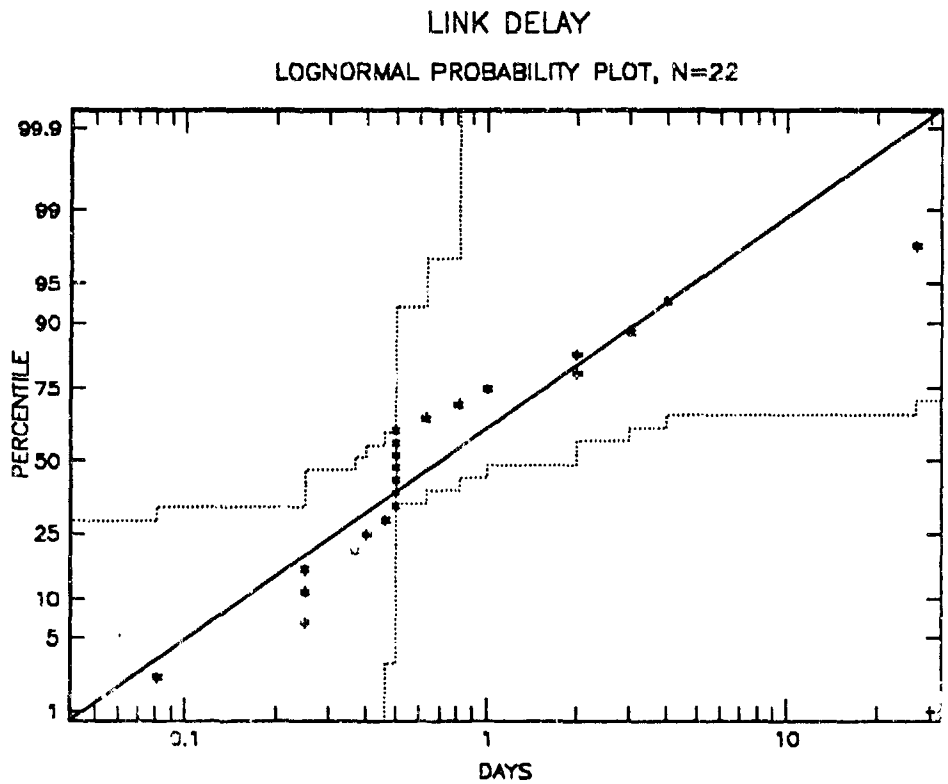

Figure 41. Link Delay Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : LINK
SELECTION : ALL
X AXIS LABEL: DAYS
SAMPLE SIZE : 22
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.351	0.88451	0.1825	0.062811	0
SIGMA	1.1755	0.92567	1.7195	0	0.031405

	SAMPLE	FITTED
MEAN :	2.091	1.4048
STD DEV :	5.6498	2.426
SKEWNESS:	4.1585	10.331
KURTOSIS:	18.856	422.36

PERCENTILES	SAMPLE	FITTED
5.	0.25	0.10178
10:	0.25	0.1560[illegible]
25:	0.4	0.31869
50:	0.5	0.70398
75:	1	1.5551
90:	3	3.1762
95:	4	4.8694

GOODNESS OF FIT

KOLM-SMIRN	:	0.25086
SIGNIF	:	0.12542
CRAMER-V M	:	0.23969
SIGNIF	:	> .15
ANDER-DARL	:	1.2127
SIGNIF	:	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

APPENDIX E. REPAIR TIME FITS

A. STARTER

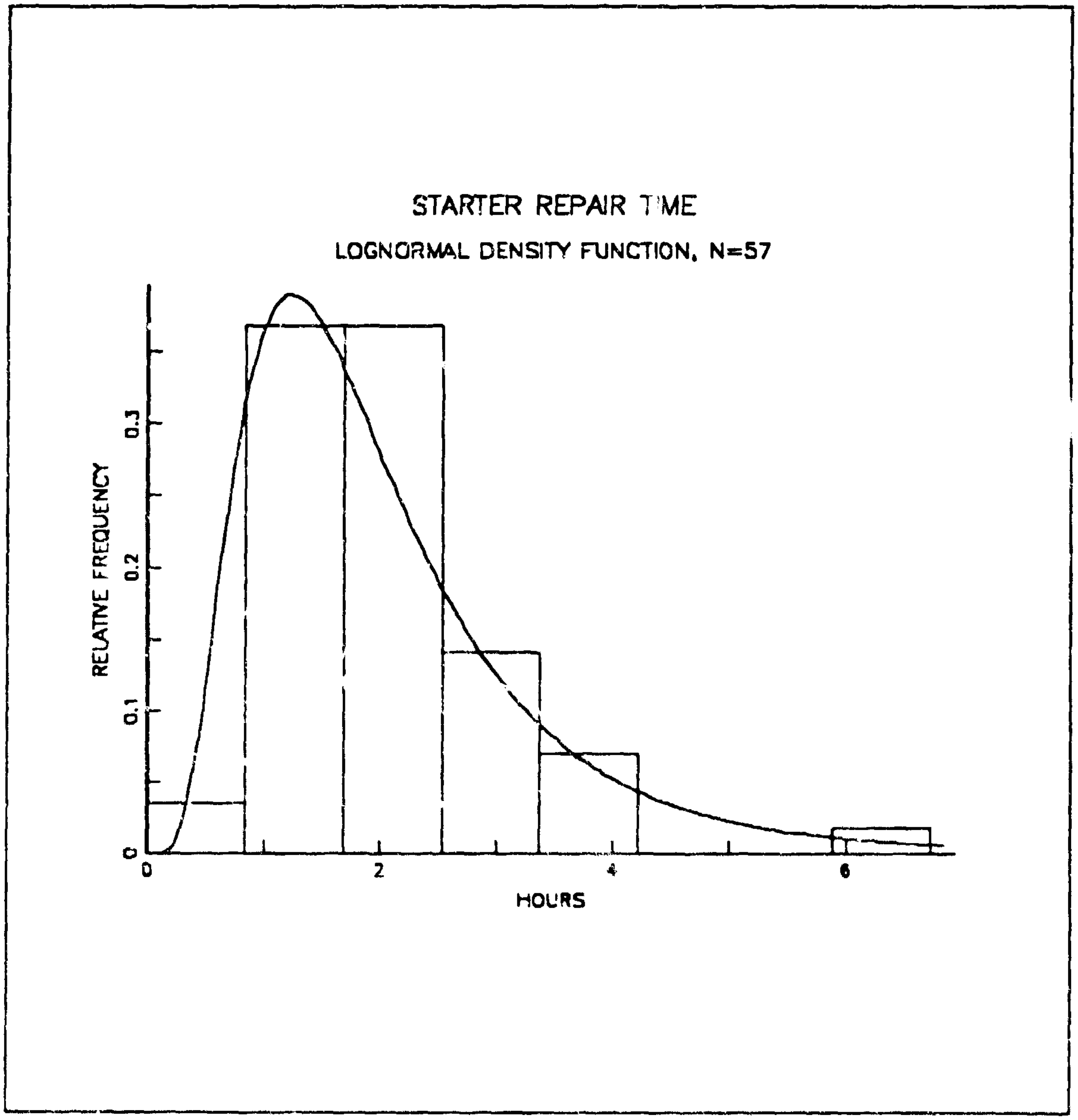

Figure 42. Starter Repair Histogram

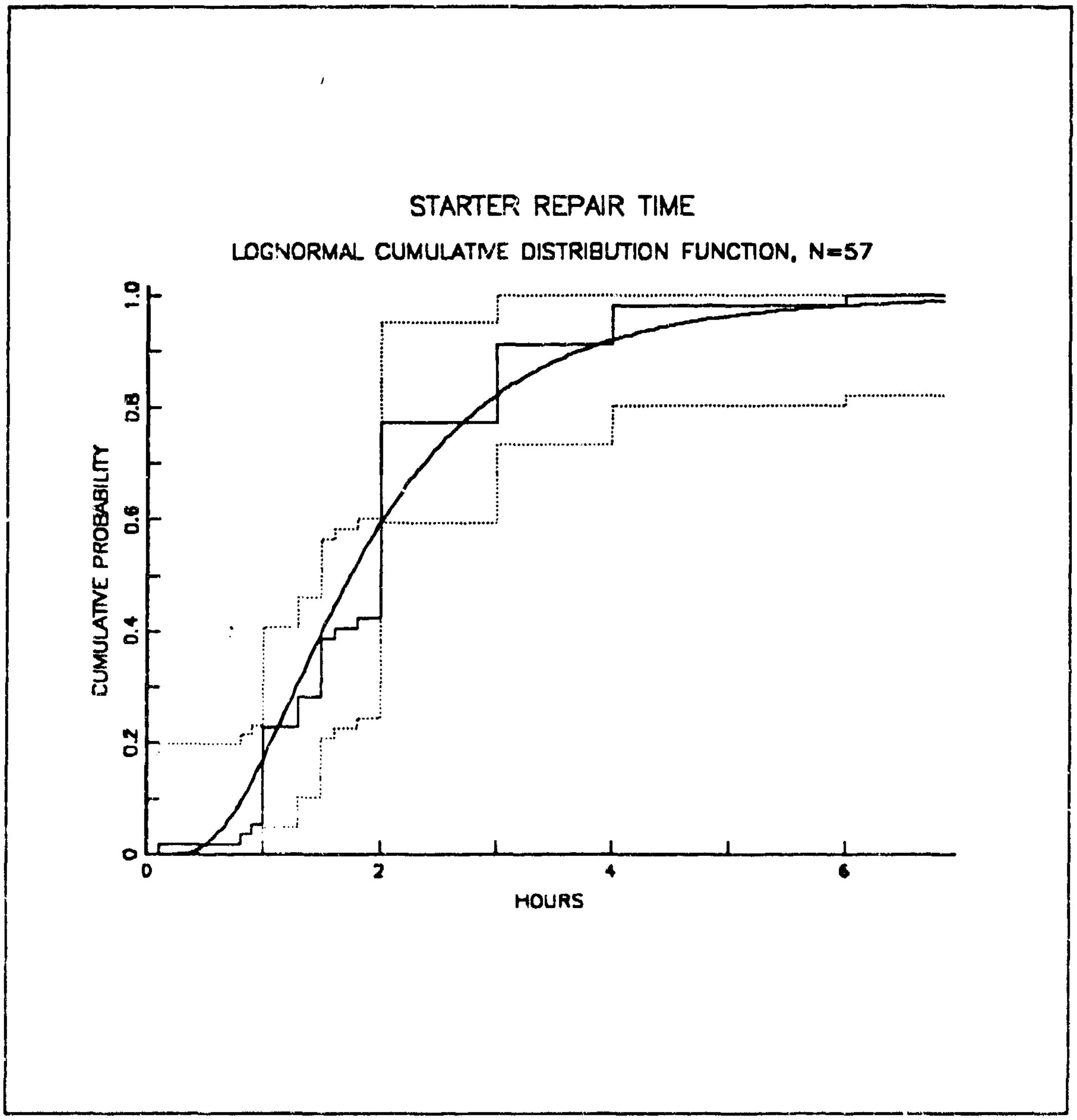

Figure 43. Starter Repair Distribution Fit

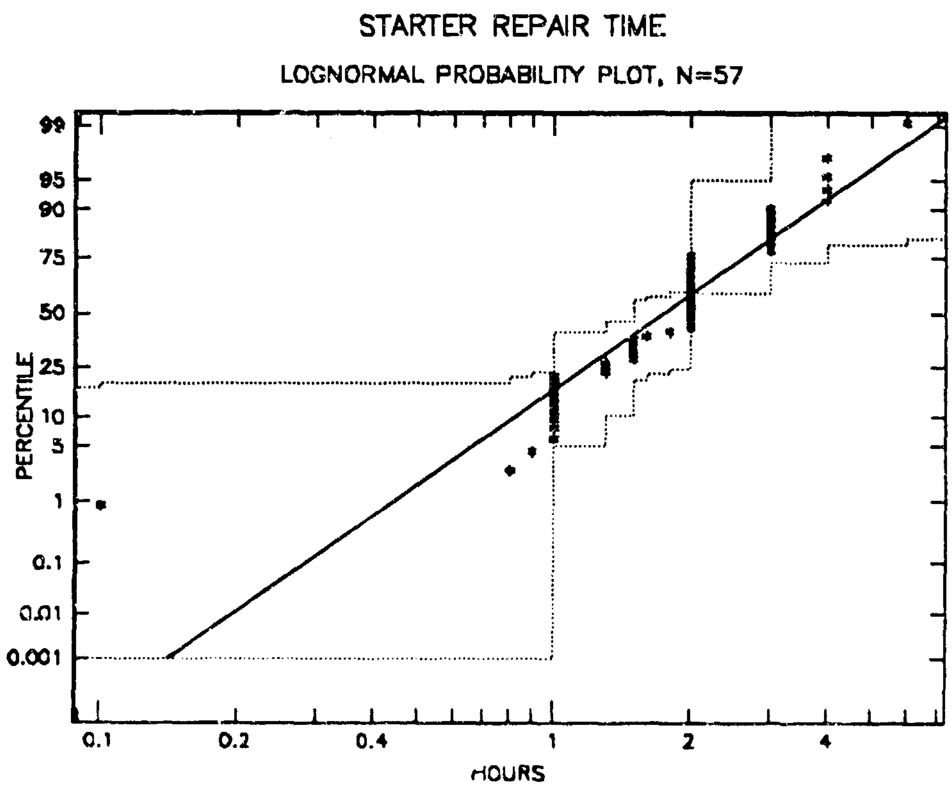

Figure 44. Starter Repair Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : STARTER
SELECTION : ALL
X AXIS LABEL: HOURS
SAMPLE SIZE : 57
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.55501	0.39739	0.71262	0.0060716	0
SIGMA	0.58829	0.50106	0.72818	0	0.0030358

	SAMPLE	FITTED
MEAN :	2.0018	2.071
STD DEV :	1.0302	1.3318
SKEWNESS:	1.3499	2.1951
KURTOSIS:	5.7311	12.635

PERCENTILES	SAMPLE	FITTED
5:	0.9	0.66176
10:	1	0.81954
25:	1.3	1.1716
50:	2	1.742
75:	2	2.5899
90:	3	3.7026
95:	4	4.5853

GOODNESS OF FIT

CHI-SQUARE :	7.5867
DEG FREED:	3
SIGNIF :	0.055365
KOLM-SMIRN :	0.1791
SIGNIF :	0.051622
CRAMER-V M :	0.33067
SIGNIF :	< .15
ANDER-DARL :	1.9312
SIGNIF :	< .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)*2)*E
-INF.	0.84286	2	6.1899	4.1899	2.8361
0.84286	1.6857	21	21.042	0.042197	0.000084615
1.6857	2.5286	21	14.764	6.2357	2.6337
2.5286	3.3714	8	7.5461	0.45387	0.027299
3.3714	4.2143	4	3.6625	0.33747	0.031094
4.2143	+INF.	1	3.7949	2.7949	2.0554
TOTAL		57	57		7.5867

B. LINK

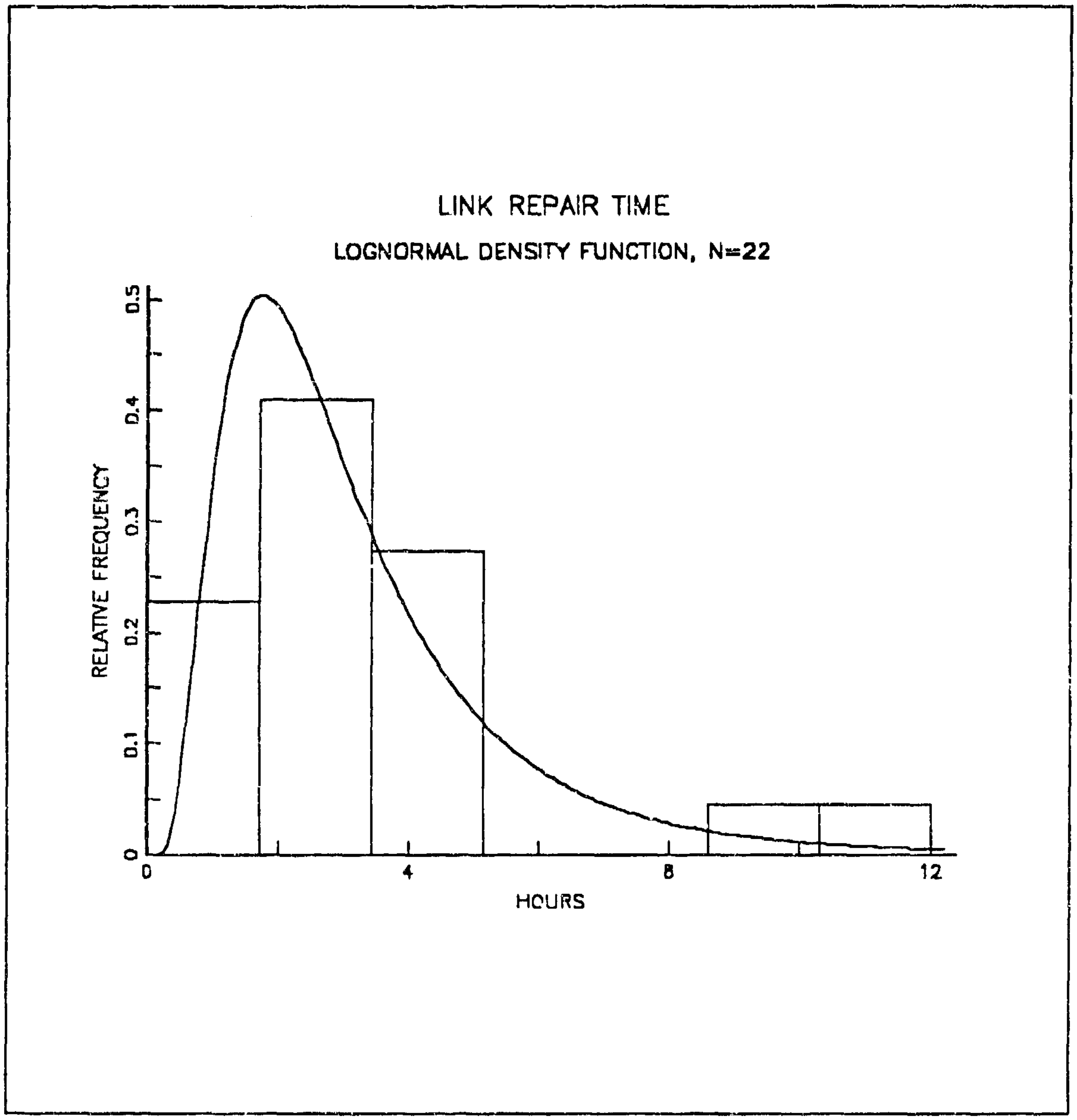

Figure 45. Link Repair Histogram

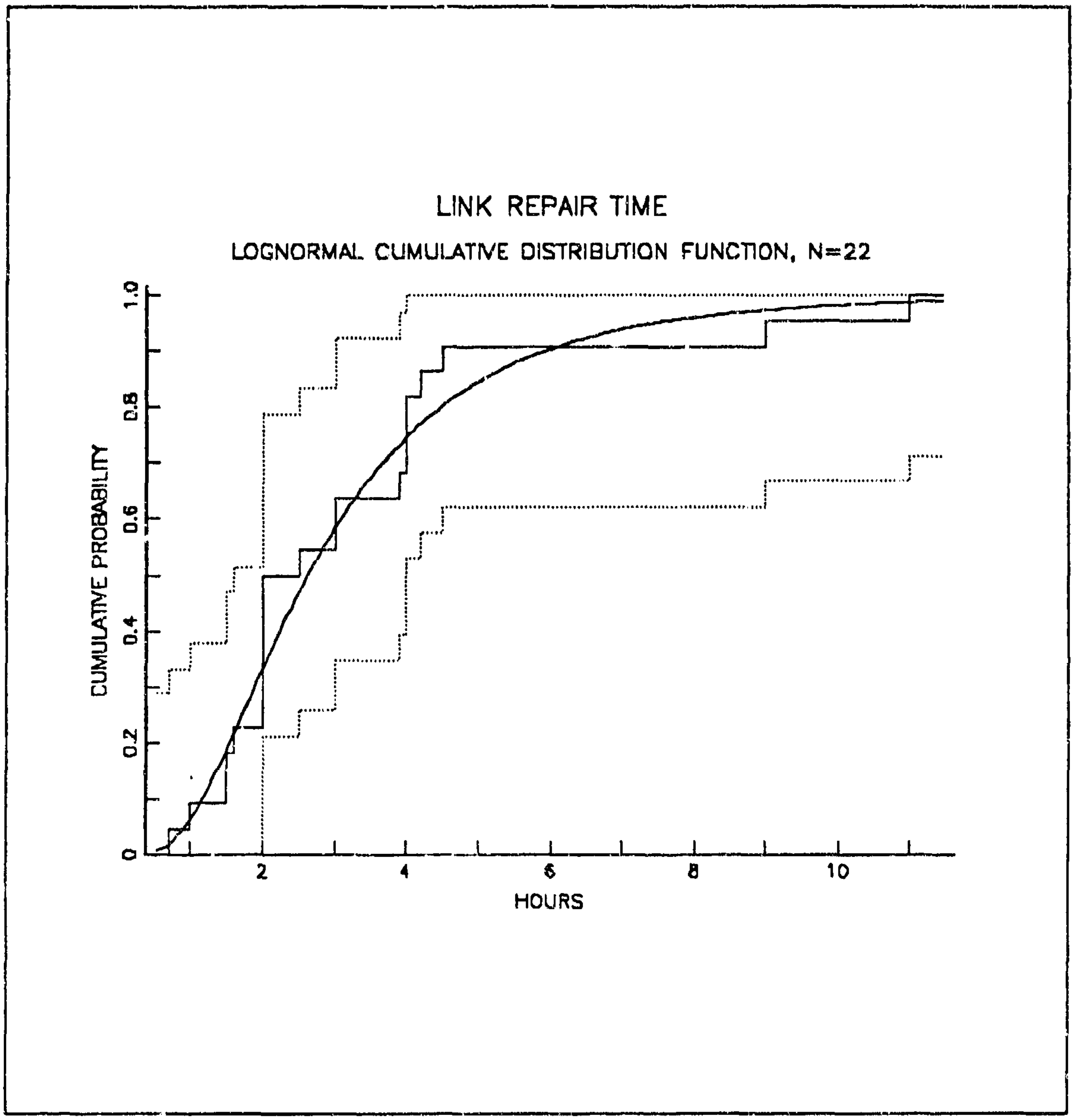

Figure 46. Link Repair Distribution Fit

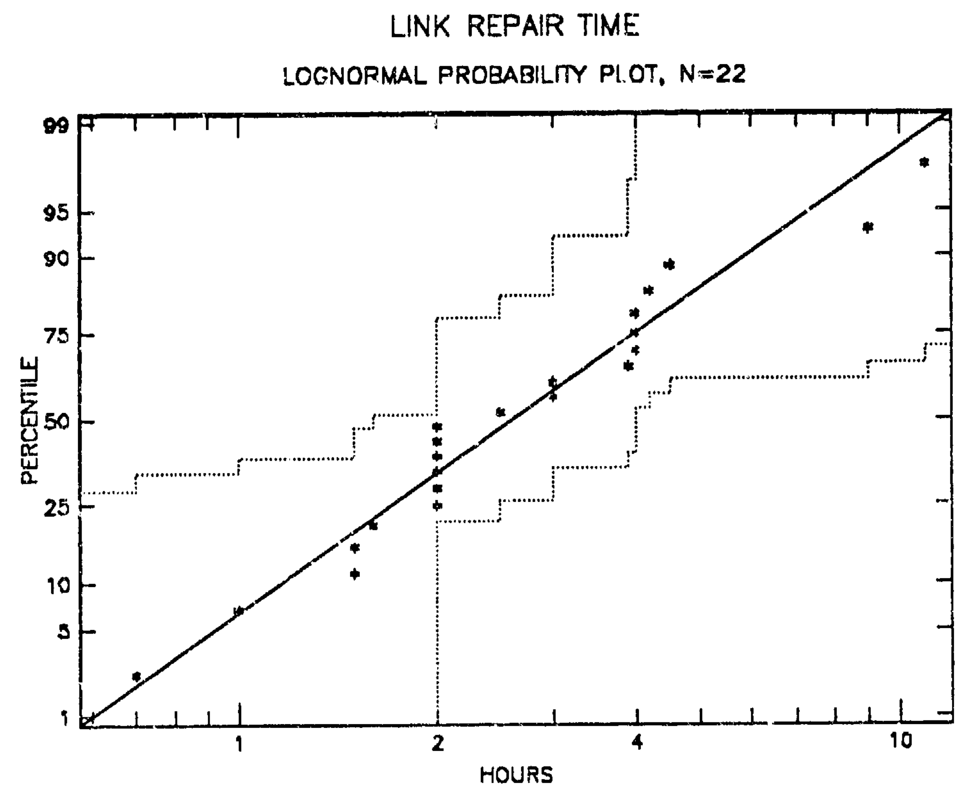

Figure 47. Link Repair Percentile Plot

ANALYSIS OF LOGNORMAL DISTRIBUTION FIT

DATA : LINK
SELECTION : ALL
X AXIS LABEL: HOURS
SAMPLE SIZE : 22
CENSORING : NONE
FREQUENCIES : 1
EST. METHOD : MAXIMUM LIKELIHOOD
CONF METHOD : EXACT

		CONF. INTERVALS (95 PERCENT)		COVARIANCE MATRIX OF PARAMETER ESTIMATES	
PARAMETER	ESTIMATE	LOWER	UPPER	MU	SIGMA
MU	0.96595	0.67886	1.253	0.018188	0
SIGMA	0.63257	0.49812	0.92531	0	0.0090941

	SAMPLE	FITTED
MEAN :	3.2455	3.2092
STD DEV :	2.4705	2.2511
SKEWNESS:	1.9599	2.4495
KURTOSIS:	6.4614	15.277

PERCENTILES	SAMPLE	FITTED
5:	1	0.92796
10:	1.5	1.1679
25:	2	1.7151
50:	2.25	2.6273
75:	4	4.0246
90:	4.5	5.9105
95:	9	7.4384

GOODNESS OF FIT

CHI-SQUARE :	1.2108
DEG FREED:	1
SIGNIF :	0.27117
KOLM-SMIRN :	0.16686
SIGNIF :	0.57263
CRAMER-V M :	0.079711
SIGNIF :	> .15
ANDER-DARL :	0.47637
SIGNIF :	> .15

KS, AD, AND CV SIGNIF. LEVELS NOT EXACT WITH ESTIMATED PARAMETERS.

CHI-SQUARE GOODNESS OF FIT TABLE

LOWER	UPPER	OBS	EXP	O-E	((O-E)*2)*E
-INF.	1.7167	5	5.5122	0.51216	0.047586
1.7167	3.4333	9	9.0927	0.092724	0.00094556
3.4333	5.15	6	4.2345	1.7655	0.7361
5.15	+INF.	2	3.1606	1.1606	0.4262
TOTAL		22	22		1.2108

APPENDIX F. PROGRAM USED TO DETERMINE AGE REPLACEMENT AND COST

Code: APL

Programmer: O. Uyar, provided by author of [Ref. 11]

Date: August 1990

```
      ∇ SIM;C1;C2;I;J;FX;X;T;XA;YA;C;XMIN;YMIN
-1-    ⍝ THIS PROGRAM SIMULATES THE COST FUNCTION (EQUATION 2.4) TO FIND
-2-    ⍝ MINIMUM VALUE (YMIN) OF THE COST FUNCTION AND CORRESPONDING AGE.
-3-    ⍝ REPLACEMENT TIME (XMIN) FOR THAT POINT.  AFTER FINDING MINIMUM
[4]    ⍝ VALUES INSIDE THE LOOP1 IT REPEAT THE PROCEDURE 300 TIMES INSIDE
[5]    ⍝ THE LOOP2.  FINALLY, THE PROGRAM GIVES THE AVERAGE VALUES FOR
[6]    ⍝ BOTH MINIMUM POINT AS AXST AND ACST.
[7]     T←(⍳5000)÷100
-8-    ⍝ THIS GIVES US A VECTOR OF T(0.01, 0.02, ..., 50) TO CALCULATE
[9]    ⍝ FIRST C(0.01) AND THEN C(0.02) UP TO C(50) OF 5000 COST VECTOR.
[10]   ⍝ INITIALIZATION...
[11]   ⍝ UNPLANNED AND PLANNED REPLACEMENT COST MUST BE GIVEN BY THE USER.
[12]    C1←5
[13]    C2←1
```

```
[14]  XA←⍳0
[15]  YA←⍳0
[16]  J←0
[17] ⍝ J IS THE INCREMENT OF THE LOOP2 J=1, 2, ...,300
[18] ⍝ MODEL...
[19] LOOP2:
[20]  X←5000 WEIRAND 2 2.2567587
[21] ⍝ LINE 14, GENERATES 5000 SYSTEM LIFETIMES FROM
[22] ⍝ WEI( ALPHA=2.0 , BETA=2.2567587 )AS VECTOR X.  HERE BETA VALUE
[23] ⍝ REPRESENTS 1 OVER LAMBDA=( 1÷0.44311346 ).
[24] ⍝ FOR GAMMA DISTRIBUTION LINE 14 CAN BE SWITCH WITH
[25]   X←5000 WEIRAND 4 0.5 FOR GAMMA ( P=4 , THETA=0.5 ).
[26]  J←J+1
[27]  C←⍳0
[28]  I←0
[29] ⍝ I IS THE INCREMENT OF THE INNER LOOP I=1, 2, ...,5000
[30] LOOP1:
[21]  I←I+1
[32] ⍝ C IS THE SIMULATED COST FUNCTION
[33]  C←C,(((C2×(1-FX))+(C1×(FX←((+/X≤T[I])÷5000))))÷((+/(X⌊T[I]))
-34- ⍝ IN THE FIRST LOOP C VECTORS OBTAIN FOR EACH T
[35]  →(I<5000)/LOOP1
[36]  YMIN←⌊/C
[37]  XMIN←T[1↑⍋C]
```

```
[38] ⍝ YMIN : THE MINIMUM VALUE OF THE COST FUNCTION FOR SPECIFIC T
[39] ⍝ XMIN : THE CORRESPONDING AGE REPLACEMENT TIME (T)
[40]  XA←XA,XMIN
[41]  YA←YA,YMIN
[42] ⍝ XA : THE VECTOR OF THE AGE REPLACEMENT TIMES (300)
[43] ⍝ YA : THE VECTOR OF THE YMIN (300)
[44]  →(J<300)/LOOP2
[45]  AXST←(+/XA)÷⍴XA
[46]  ACST←(+/YA)÷⍴YA
-47- ⍝ AXST : THE AVERAGE VALUE OF THE AGE REPLACEMENT TIMES AFTER 300 REP.
-48- ⍝ ACST : THE AVERAGE VALUE OF THE YMIN AFTER 300 REPEATITIONS.
     ∇
```

APPENDIX G. SCALED TIME ON TEST PLOT PROCEDURE AND APL CODE

Code: APL

Programmer: J. Wilhelm

Date: August 1990

```
STEPS

1) MAKE A 101 UNIT VECTOR FROM 0 TO MAXIMUM
 MILAGE WITH INTERVALS H.

XX← 0,H×(⍳100)

2) USE THE XX VECTOR TO FIND A WEIBULL CDF
 VECTOR.

P←SHAPE SCALE WEICDF XX

3) CALCULATE THE SURVIVAL VECTOR

FBAR← 1 - P


STARTER INPUTS

H← 200

XX← 0,200×(⍳100)

P←1.1999 4689.7 WEICDF XX

FBAR← 1 - P
```

```
LINK INPUTS

H← 300

XX← 0,300×(⍳100)

P←1.2801 10239. WEICDF XX

FBAR← 1 - P
```

4) RUN THIS PROGRAM TO INTEGRATE THE SURVIVOR FUNCTION FROM 0 TO EACH POINT IN THE VECTOR. THE RESULT IS A VECTOR K.

```
      ∇BLDG [⎕] ∇

      ∇ BLDG
[1]   I←2
[2]   K←0
[3]  LOOP:→ENDLOOP IF I>101
[4]   PART←I↑FBAR
[5]   J←H SIMPSON PART
[6]   K←K,J
[7]   I←I+1
[8]   →LOOP
[9]  ENDLOOP:
[10]
      ∇
```

5) *STANDARDIZE K WITH THE MEAN.*

```
STD← K ÷ 4411.4
```

RESULTS

STARTER

```
STD← K ÷ 4411.4
```

LINK

```
STD← K ÷ 9486.9
```

6) *PLOT STD VERSUS P TO OBTAIN THE SCALED TIME ON TEST.*

APPENDIX H. COMPONENT SIMULATION

Code: SIMSCRIPT II.5

Programmer: J. Wilhelm

Date: August 1990

```
'' PART RAM  MODEL

PREAMBLE
NORMALLY, MODE IS UNDEFINED
DEFINE .MILES TO MEAN MINUTES
PROCESSES INCLUDE STOP.SIM AND PART
   DEFINE FAIL.SHAPE AS A REAL VARIABLE
   DEFINE FAIL.SCALE AS A REAL VARIABLE
   DEFINE DELAY.MU  AS A REAL VARIABLE
   DEFINE DELAY.SIG AS A REAL VARIABLE
   DEFINE REP.MU  AS A REAL VARIABLE
   DEFINE REP.SIG AS A REAL VARIABLE
   DEFINE SEED1 AND SEED2 AS INTEGER VARIABLES
   DEFINE SEED3 AS A  INTEGER VARIABLE
   DEFINE NO.OF.PARTS AND NO.FAIL AS INTEGER VARIABLES
   DEFINE REPL.NO AS A INTEGER VARIABLE
   DEFINE N AS A INTEGER VARIABLE
   DEFINE NOW.WORK AS A INTEGER VARIABLE
   DEFINE PRCNT.UP AS A REAL VARIABLE
   DEFINE T.FAIL AS A INTEGER VARIABLE
   DEFINE RUN.LENGTH AS A REAL VARIABLE
   DEFINE MILES.T AS A REAL VARIABLE
   DEFINE MILES.N AS A REAL VARIABLE
```

```
    DEFINE DOWN.T AS A REAL VARIABLE
    DEFINE DOWN.N AS A REAL VARIABLE
    DEFINE PART.COST AS A REAL VARIABLE
    DEFINE STAND.BY.COST AS A REAL VARIABLE
    DEFINE MN.HR.COST AS A REAL VARIABLE
    DEFINE PEN.COST AS A REAL VARIABLE
    DEFINE REP.COST AS A REAL VARIABLE
    DEFINE TOT.COST AS A REAL VARIABLE
    DEFINE D.COST AS A REAL VARIABLE
    DEFINE R.COST AS A REAL VARIABLE
    DEFINE T.COST AS A REAL VARIABLE
    TALLY AVG.MILES.T AS THE MEAN,
          SIG.MILES.T AS THE STD.DEV OF MILES.T
    TALLY AVG.DOWN.T AS THE MEAN,
          SIG.DOWN.T AS THE STD.DEV OF DOWN.T
    TALLY AVG.T.FAIL AS THE MEAN,
          SIG.T.FAIL AS THE STD.DEV OF T.FAIL
    TALLY AVG.R.COST AS THE MEAN,
          SIG.R.COST AS THE STD.DEV OF R.COST
    TALLY AVG.D.COST AS THE MEAN,
          SIG.D.COST AS THE STD.DEV OF D.COST
    TALLY AVG.T.COST AS THE MEAN,
          SIG.T.COST AS THE STD.DEV OF T.COST
    ACCUMULATE AVAIL AS THE AVERAGE OF NOW.WORK

END

MAIN
    LET MINUTES.V = 6.5373 / 24.  ''MILES
    CALL READ.DATA
    FOR N = 1 TO 5000,DO
    CALL INITIALIZE
    ACTIVATE A STOP.SIM IN RUN.LENGTH DAYS
    START SIMULATION
```

```
    LOOP
END

ROUTINE INITIALIZE
            '' STARTER
        ''  CREATE A PART
        ''  LET FAIL.SHAPE = 1.1999
        ''  LET FAIL.SCALE = 4689.7
        ''  LET DELAY.MU  = .59102
        ''  LET DELAY.SIG = .79943
        ''  LET REP.MU  = .55501
        ''  LET REP.SIG = .58829
        ''  LET SEED1 = 8
        ''  LET SEED2 = 2
        ''  LET SEED3 = 4
        ''  PART.COST = 794.
    ''**********
            '' LINK
            CREATE A PART
            LET FAIL.SHAPE = 1.2801
            LET FAIL.SCALE = 10239.0
            LET DELAY.MU  = .3510
            LET DELAY.SIG = 1.1755
            LET REP.MU  = .96595
            LET REP.SIG = .63257
            LET SEED1 = 9
            LET SEED2 = 1
            LET SEED3 = 5
            PART.COST = 488.
        ''*******
            ACTIVATE THIS PART NOW

END
```

```
ROUTINE READ.DATA
        NO.OF.PARTS = 1
'' PRINT 1 LINE THUS
''  HOW LONG SHALL WE RUN (IN DAYS)?
'' READ RUN.LENGTH
        RUN.LENGTH =  730.0  ''730 DAYS IN TWO YEAR OR 7300 IN 20
        STAND.BY.COST = 1781. ''PENALTY COST PER DAY
        MN.HR.COST = 50.   '' COST PER REPAIR HOUR
END


PROCESS PART
   DEFINE TTF AS A REAL VARIABLE ''TIME TO FAILURE
   DEFINE RT AS A REAL VARIABLE  ''REPAIR TIME
   DEFINE DT AS A REAL VARIABLE  ''DELAY TIME
   DEFINE RC AS A REAL VARIABLE  ''REPAIR COST PER REPLACEMENT
   DEFINE DC AS A REAL VARIABLE  ''DELAY COST  PER INCIDENT
   DEFINE TC AS A REAL VARIABLE  ''TOTAL COST  PER INCIDENT
   UNTIL TIME.V >= RUN.LENGTH
   DO
      ADD 1 TO NOW.WORK
  ''  WORK WEIBULL.F(FAIL.SHAPE,FAIL.SCALE,SEED1).MILES    TIME TO FAIL
      LET TTF = WEIBULL.F(FAIL.SHAPE,FAIL.SCALE,SEED1)  ''
      IF TTF  > 15450
       '' PRINT 1 LINE WITH NO.FAIL  THUS
       ''  *****   SKED REPLACE EARLY
          TTF = 15450
          WORK TTF .MILES ''UNTIL FAILURE TIME
          SUBTRACT 1 FROM NOW.WORK
       '' PRINT 1 LINE WITH NO.FAIL  THUS
       ''  *****   PART REPLACED EARLY
          ADD 1 TO REPL.NO
          LET RT = LOG.NORMAL.F(REP.MU,REP.SIG,SEED3)
          LET RC = PART.COST + (MN.HR.COST * RT)
```

```
            ADD RC TO REP.COST
            WAIT RT HOURS    ''TIME TANK UNAVAILABLE
            LET DC = (STAND.BY.COST/24) * RT
            ADD DC TO PEN.COST
            LET TC = RC + DC
            ADD TC TO TOT.COST
            CYCLE
        ALWAYS
        WORK TTF .MILES ''UNTIL FAILURE TIME
        SUBTRACT 1 FROM NOW.WORK
        ADD 1 TO NO.FAIL
        LET RT = LOG.NORMAL.F(REP.MU,REP.SIG,SEED3)    ''
        LET RC = PART.COST + (MN.HR.COST * RT)
        ADD RC TO REP.COST
    ''  WAIT LOG.NORMAL.F(DELAY.MU,DELAY.SIG,SEED2) DAYS      DELAY TIME
        LET DT = LOG.NORMAL.F(DELAY.MU,DELAY.SIG,SEED2)    ''
        WAIT DT DAYS    ''TIME TANK UNAVAILABLE
        LET DC = STAND.BY.COST * DT
        ADD DC TO PEN.COST
        LET TC = RC + DC
        ADD TC TO TOT.COST
      LOOP
END


PROCESS STOP.SIM

        LET T.FAIL..= NO.FAIL
        LET PRCNT.UP..  = AVAIL
        LET R.COST..= REP.COST
        LET D.COST..= PEN.COST
        LET T.COST..= TOT.COST
  ''******
  ''PRINT 1 LINE WITH N AND TIME.V THUS
```

```
''*    **.** :
''PRINT 1 LINE WITH NO.FAIL THUS
''    *****    FAILED
''PRINT 1 LINE WITH AVAIL*100/N THUS
''   ***.****  PERCENT AVAIL
''PRINT 1 LINE WITH REP.COST THUS
''   ***.****  COST REP
''PRINT 1 LINE WITH PEN.COST THUS
''   ***.****  COST PEN
''PRINT 1 LINE WITH TOT.COST THUS
''   ***.****  COST TOTAL
''*********
'' PRINT 1 LINE WITH N,MILES.N,DOWN.N , NO.FAIL AND AVG.DOWN.T THUS
'' *    **.**   **.**   **    **.**
    TIME.V = 0.0
''  DOWN.N = 0.0
''  MILES.N = 0.0
    NO.FAIL = 0
    REP.COST = 0.0
    PEN.COST = 0.0
    TOT.COST = 0.0

      DESTROY THIS PART
'' PRINT 1 LINE WITH TIME.V  THUS
''     **.**     DAYS
'' PRINT 1 LINE WITH DOWN.T  THUS
''     **.**     DAYS DOWN
'' PRINT 1 LINE WITH MILES.T  THUS
''     **.**     MILES
'' PRINT 1 LINE WITH NO.FAIL THUS
''     *****     FAILED
  IF N >= 5000
   CALL LAST.RUN
  ALWAYS
```

```
END

ROUTINE LAST.RUN
  PRINT 1 LINE WITH N THUS
  FOR **** RUNS
  PRINT 1 LINE WITH REPL.NO THUS
   ****  PARTS REPLACED EARLY UNDER POLICY.
  PRINT 1 LINE WITH AVG.T.FAIL AND SIG.T.FAIL THUS
  AND AVERAGED *****.** FAILURES WITH STD.DEV= ****.** IN      YEARS.
  PRINT 1 LINE WITH AVG.R.COST AND SIG.R.COST THUS
  AND AVERAGED *******.** REPAIR COST WITH STD.DEV= ******.**
  PRINT 1 LINE WITH AVG.D.COST AND SIG.D.COST THUS
  AND AVERAGED *******.** PENALTY COST WITH STD.DEV= ******.**
  PRINT 1 LINE WITH AVG.T.COST AND SIG.T.COST THUS
  AND AVERAGED *******.** TOTAL COST WITH STD.DEV= ******.**
  PRINT 1 LINE WITH PRCNT.UP*100/N THUS
     ***.****  PERCENT AVAILABLE
  STOP
END
```

APPENDIX I. SYSTEM SIMULATION

Code: SIMSCRIPT II.5

Programmer: J. Wilhelm

Date: July 1990

```
'' TANK RAM  MODEL

PREAMBLE
NORMALLY, MODE IS UNDEFINED
DEFINE .MILES TO MEAN HOURS
PROCESSES INCLUDE TANK.DOWN AND STOP.SIM
   EVERY PART
      BELONGS TO A PART.SET
      AND HAS A FAIL.SHAPE
      AND HAS A FAIL.SCALE
      AND HAS A DELAY.MU
      AND HAS A DELAY.SIG
      AND HAS A SEED1
      AND HAS A SEED2
   DEFINE FAIL.SHAPE AS A REAL VARIABLE
   DEFINE FAIL.SCALE AS A REAL VARIABLE
   DEFINE DELAY.MU  AS A REAL VARIABLE
   DEFINE DELAY.SIG AS A REAL VARIABLE
   DEFINE SEED1 AND SEED2 AS INTEGER VARIABLES

THE SYSTEM OWNS THE PART.SET
   DEFINE NO.OF.PARTS AND NO.FAIL AS INTEGER VARIABLES
   DEFINE N AS A INTEGER VARIABLE
```

```
    DEFINE T.FAIL AS A INTEGER VARIABLE
    DEFINE RUN.LENGTH AS A REAL VARIABLE
    DEFINE MILES.T AS A REAL VARIABLE
    DEFINE MILES.N AS A REAL VARIABLE
    DEFINE DOWN.T AS A REAL VARIABLE
    DEFINE DOWN.N AS A REAL VARIABLE
    TALLY AVG.MILES.T AS THE MEAN,
          SIG.MILES.T AS THE STD.DEV OF MILES.T
    TALLY AVG.DOWN.T AS THE MEAN,
          SIG.DOWN.T AS THE STD.DEV OF DOWN.T
    TALLY AVG.T.FAIL AS THE MEAN,
          SIG.T.FAIL AS THE STD.DEV OF T.FAIL
END

MAIN
    LET HOURS.V = 6.5373  ''MILES
    CALL READ.DATA
    FOR N = 1 TO 5,DO
    CALL INITIALIZE
    ACTIVATE A STOP.SIM IN RUN.LENGTH DAYS
    START SIMULATION
    LOOP
END

ROUTINE INITIALIZE
 ''DEFINE I AS A INTEGER VARIABLE
      CREATE A TANK.DOWN

    '' FOR I = 1 TO NO.OF.PARTS
    '' DO
          '' STARTER
          CREATE A PART
          LET FAIL.SHAPE(PART) = 1.1999
          LET FAIL.SCALE(PART) = 4689.7
```

```
LET DELAY.MU (PART) = .59102
LET DELAY.SIG(PART) = .79943
LET SEED1(PART) = 1
LET SEED2(PART) = 2
FILE THIS PART IN THE PART.SET
ACTIVATE THIS PART NOW
'' FUEL NOZZLE
CREATE A PART
LET FAIL.SHAPE(PART) = 1.3384
LET FAIL.SCALE(PART) = 4438.7
LET DELAY.MU (PART) = .69437
LET DELAY.SIG(PART) = .67156
LET SEED1(PART) = 3
LET SEED2(PART) = 4
FILE THIS PART IN THE PART.SET
ACTIVATE THIS PART NOW
'' DIST BOX
CREATE A PART
LET FAIL.SHAPE(PART) = 1.5315
LET FAIL.SCALE(PART) = 6858.6
LET DELAY.MU (PART) = .57369
LET DELAY.SIG(PART) = .93421
LET SEED1(PART) = 5
LET SEED2(PART) = 6
FILE THIS PART IN THE PART.SET
ACTIVATE THIS PART NOW
'' TRANS
CREATE A PART
LET FAIL.SHAPE(PART) = 1.4455
LET FAIL.SCALE(PART) = 7479.5
LET DELAY.MU (PART) = .15064
LET DELAY.SIG(PART) = .94184
LET SEED1(PART) = 7
LET SEED2(PART) = 8
```

```
        FILE THIS PART IN THE PART.SET
        ACTIVATE THIS PART NOW
        '' LINK
        CREATE A PART
        LET FAIL.SHAPE(PART) = 1.2801
        LET FAIL.SCALE(PART) = 10239.0
        LET DELAY.MU (PART) = .3510
        LET DELAY.SIG(PART) = 1.1755
        LET SEED1(PART) = 9
        LET SEED2(PART) = 1
        FILE THIS PART IN THE PART.SET
        ACTIVATE THIS PART NOW
        '' GRIP
        CREATE A PART
        LET FAIL.SHAPE(PART) = 1.5539
        LET FAIL.SCALE(PART) = 4369.9
        LET DELAY.MU (PART) = .60291
        LET DELAY.SIG(PART) = .87986
        LET SEED1(PART) = 2
        LET SEED2(PART) = 3
        FILE THIS PART IN THE PART.SET
        ACTIVATE THIS PART NOW
  ''    LET FAIL.SHAPE(PART) = 1.0
  ''    LET FAIL.SCALE(PART) = 5.0
  ''    LET DELAY.MU (PART) = 2.4
  ''    LET DELAY.SIG(PART) = 1.0
  ''    LET SEED1(PART) = 1
  ''    LET SEED2(PART) = 1
  '' LOOP
     ACTIVATE A TANK.DOWN NOW
  '' ACTIVATE A UP.TANK NOW
  '' LET FAIL.SCALE(1) = 5.0

END
```

```
ROUTINE READ.DATA
'' PRINT 1 LINE THUS
''  HOW MANY TANKS?
'' READ NO.OF.TANKS
''      NO.OF.TANKS = 1
'' PRINT 1 LINE THUS
''  HOW MANY PARTS PER TANK?
'' READ NO.OF.PARTS
        NO.OF.PARTS = 6
'' PRINT 1 LINE THUS
''  HOW LONG SHALL WE RUN (IN DAYS)?
'' READ RUN.LENGTH
        RUN.LENGTH =  7300.0
 ''     DOWN.T = 0.0
 ''     MILES.N = 0.0
 ''     LET FAIL.SCALE.. = 5.0
 ''     FAIL.SCALE(2) = 5.0
END


PROCESS PART
   UNTIL TIME.V >= RUN.LENGTH
   DO
      WORK WEIBULL.F(FAIL.SHAPE,FAIL.SCALE,SEED1).MILES  ''TIME TO FAIL
      REACTIVATE THE TANK.DOWN NOW
      WAIT LOG.NORMAL.F(DELAY.MU,DELAY.SIG,SEED2) DAYS  '' REPAIR TIME
      REACTIVATE THE TANK.DOWN NOW
   LOOP
'' IF TIME.V <= RUN.LENGTH
''    REMOVE THIS PART FROM THE PART.SET
'' ALWAYS
'' SUSPEND
END
```

```
PROCESS TANK.DOWN
   DEFINE FAIL.T AS A REAL VARIABLE
     FAIL.T = 0.0
   DEFINE REPAIR.T AS A REAL VARIABLE
     REPAIR.T = 0.0
   UNTIL TIME.V >= RUN.LENGTH
   DO
      SUSPEND ''AWAITING A SUBASSEBLY  FAILURE
      LET FAIL.T = TIME.V
   '' INTERRUPT UP.TANK
      FOR EACH PART IN THE PART.SET,
         WITH STA.A(PART) = 1 ''I.E.,IT IS OPERATING
      DO
         INTERRUPT THIS PART
      LOOP
      ADD 1 TO NO.FAIL
      SUSPEND ''AWAITING REPLACEMENT OF SUASSEMBLY
      LET REPAIR.T = TIME.V - FAIL.T
      LET DOWN.N = DOWN.N + REPAIR.T
      LET DOWN.T = DOWN.N
   '' LET MILES.T..= 1 * (TIME.V - DOWN.T)
   '' RESUME UP.TANK
      FOR EACH PART IN THE PART.SET,
          WITH M.EV.S(PART) <> 1 ''I.E.,IT IS NOT SCHEDULED
      DO
         RESUME THIS PART
      LOOP
   LOOP
   SUSPEND ''AWAITING END OF SIMULATION

END
```

```
PROCESS STOP.SIM

      LET MILES.N..= 6.5373 * (TIME.V - DOWN.T)
      LET MILES.T..= 6.5373 * (TIME.V - DOWN.T)
      LET T.FAIL..= NO.FAIL
'' PRINT 1 LINE WITH N AND TIME.V THUS
'' *    **.**
'' PRINT 1 LINE WITH N,MILES.N,DOWN.N , NO.FAIL AND AVG.DOWN.T THUS
'' *    **.**   **.**   **    **.**
    TIME.V = 0.0
    DOWN.N = 0.0
    MILES.N = 0.0
    NO.FAIL = 0

   IF M.EV.S(TANK.DOWN) = 1
      REMOVE TANK.DOWN FROM EV.S(I.TANK.DOWN)
   '' DESTROY TANK.DOWN
   ALWAYS
   FOR EACH PART IN THE PART.SET,
      WITH M.EV.S(PART) = 1
   DO
      REMOVE THIS PART FROM EV.S(I.PART)
   LOOP
   FOR EACH PART IN THE PART.SET
   DO
      REMOVE THIS PART FROM THE PART.SET
      DESTROY THIS PART
   LOOP
'' REMOVE PART FROM EV.S(I.PART)
'' PRINT 1 LINE WITH N.EV.S (I.PART) THUS
'' *   NUM ON EV SET
   DESTROY TANK.DOWN
'' DESTROY PART
'' PRINT 1 LINE WITH TIME.V  THUS
```

```
''    **.**     DAYS
'' PRINT 1 LINE WITH DOWN.T  THUS
''    **.**     DAYS DOWN
'' PRINT 1 LINE WITH MILES.T  THUS
''    **.**     MILES
'' PRINT 1 LINE WITH NO.FAIL THUS
''    *****     FAILED
  IF N >= 5
   CALL LAST.RUN
''ELSE
'' RETURN
  ALWAYS
END

ROUTINE LAST.RUN
  PRINT 1 LINE WITH N,AVG.MILES.T AND SIG.MILES.T THUS
  FOR **** RUNS TANKS AVERAGED *****.* WITH STD.DEV= **.** (MILES)
  PRINT 1 LINE WITH AVG.DOWN.T AND SIG.DOWN.T THUS
  THEY WERE DOWN AN AVERAGE OF **.** WITH STD.DEV= **.** (DAYS)
  PRINT 1 LINE WITH AVG.T.FAIL AND SIG.T.FAIL THUS
  AND AVERAGED **.** FAILURES WITH STD.DEV= **.** IN TWO YEARS.
  STOP
END
```

LIST OF REFERENCES

1. Barlow, R. E., and Davis, B., "Analysis of Time Between Failures for Repairable Components," *Reliability and Fault Tree Analysis*, SIAM, 1982.

2. Barlow, R. E., and Proschan, F., *Statistical Theory of Reliability and Life Testing*, To Begin With, 1981.

3. Barlow, R. E., and Proschan, F., *Mathematical Theory of Reliability*, John Wiley and Sons, 1965.

4. Turnbull, B. W., "Nonparametric Estimation of a Survivorship Function with Doubly Censored Data," *Journal of the American Statistical Association 69*, pp. 169-173, 1974.

5. Blanchard, B. S., *Logistics Engineering and Management*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

6. Chung D., *Economic Analysis for the M1 Tank Inspect and Repair Only as Necessary (IRON) Program*, Draft Technical Report US Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, Maryland, June 1990.

7. Nicolas, T. and Rossi R., *US Weapon Systems Cost*, Data Search Associates, Fountain Valley, California, March 1989.

8. Beaudette, C. and Dymeki, K., *Abrams Average Annual Sustainment Cost* , Tank Automotive Command, Warren Michigan, November 1988.

9. Scwartz, T., and Wilhelm J., *Human Factors Evaluation of the M1 Abrams Driver's Station* , Report Naval Postgraduate School, Monterey, California, June 1989.

10. Foss, C., *Jane's Armour and Artillery 1989-90* , Jane's Defence Data, Alexandria Virginia, 1989.

11. Uyar O., *Sequential Estimation of Optimal Age Replacement Policies,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 1990.